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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION - SEASONAL REPORT FOR SOLARON - AKRON, AKRON, OHIO

Prepared by

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16. ABSTRACT

This report has been developed for the George C. Marshall Space Flight Center as a part of the Solar Heating and Cooling Development Program funded by the Department of Energy. It is one of a series of reports describing the operational the thermal performance of a variety of solar systems installed in Operational Test Sites under this program. The analysis used is based on instrumented system data monitored and collected for at least one full season of operation. The objective of the analysis is to report the long-term field performance of the installed system and to make technical contributions to the definition of techniques and requirements for solar energy system design.

The Solar Energy System was designed by Solaron Corporation, Denver, Colorado, to provide an 1840 square foot floor area with space heating and domestic hot water (DHW) for a dual-level single family residence in Akron, Ohio. The Solar Energy System uses air as the heat transport medium, has a 546 square foot flat plate collector array subsystem, a 270 cubic foot rock thermal storage bin subsystem, a domestic hot water preheat tank, pumps, controls and transport lines. The auxiliary space heating subsystem is an air to liquid heat pump coupled with a 1,000 gallon water storage tank. Electricity provides auxiliary energy for both space heating and DHW subsystems.

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1. FOREWORD

The Solar Energy System Performance Evaluation - Seasonal Report has been developed for the George C. Marshall Space Flight Center as a part of the Solar Heating and Cooling Development Program funded by the Department of Energy. The analysis contained in this document describes the technical performance of an Operational Test Site (OTS) functioning throughout a specified period of time which is typically one season. The objective of the analysis is to report the long term performance of the installed system and to make technical contributions to the definition of techniques and requirements for solar energy system design.

The contents of this document have been divided into the following topics of discussion:

- System Description
- Performance Assessment
- Operating Energy
- Energy Savings
- Maintenance
- Summary and Conclusions

Data used for the seasonal analyses of the Operational Test Site described in this document have been collected, processed and maintained under the OTS Development Program and have provided the major inputs used to perform the long term technical assessment. This data is archived by MSFC for DOE.

The Seasonal Report document in conjunction with the Final Report for each Operational Test Site in the Development Program culminates the technical activities which began with the site selection and instrumentation system design in April 1976. The Final Report emphasizes the economic analysis of solar systems performance and features the payback performance based on life cycle costs for the same solar system in various geographic regions. Other documents specifically related to this system are References [1] and [2].*

*Numbers in brackets designate references found in Section 8.

2. SYSTEM DESCRIPTION

The Solaron Akron Solar Energy System was designed to provide both space heating and domestic hot water (DHW) preheating for a dual level single-family residence containing approximately 1840 square feet in Akron, Ohio. Solar energy collection is accomplished with flat-plate collectors using air as the transport fluid. The collector array has a gross area of 546 square feet and faces south at an angle of 45 degrees from the horizontal. Solar energy is stored in a 270 cubic foot rock thermal storage bin located on the lower level of the house. Solar energy is transferred to the DHW subsystem by means of an in-duct heat exchanger (HX1) whenever the system is storing collected solar energy. Water from the 80 gallon preheat tank and make-up water are transferred from the preheat system to the 52 gallon DHW tank when there is a demand for hot water. The auxiliary space heating subsystem consists of an air to liquid heat pump coupled with a 1000 gallon water storage tank. The heat pump can provide energy either directly to the house or to the 1000 gallon tank. The system is designed so that the heat pump can charge the 1000 gallon tank during off-peak hours when electrical rates are lower. Energy stored in the tank can then be used for space heating purposes as required. Auxiliary energy for both the space heating and DHW subsystems is provided by electricity. The heat pump has a nominal capacity of 30,000 Btu/Hr with supplemental heat strips rated at 12 kw, and the auxiliary hot water heater is rated at 4.5 kw. The system is shown schematically in Figure 2-1, and sensor designations in Figure 2-1 are in accordance with NBSIR-76-1137 [3]. The measurement symbol prefixes: W, T, EP, and I represent respectively: flow rate, temperature, electric power, and insolation. The system has the following modes of operation:

A. First Stage

1. Collector to Storage and DHW. In this mode the collector blower transfers solar energy from the collector array to the rock thermal storage bin through the DHW heat exchanger. Part of the solar energy is utilized in the DHW preheat loop and the remaining solar energy is delivered to storage. This mode is entered

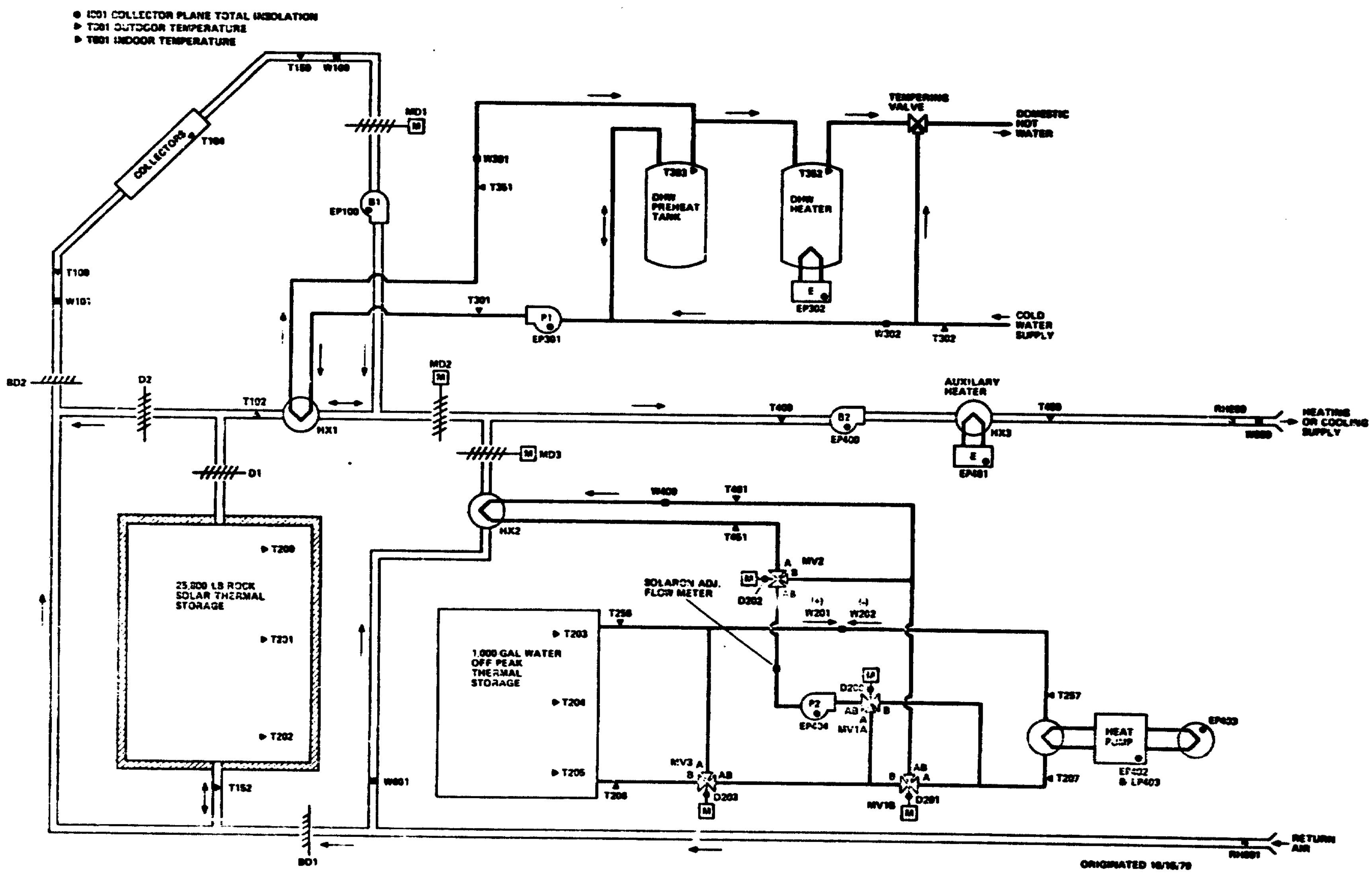

Figure 2-1 Solaron Akron Solar Energy System Schematic

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whenever the differential temperature between the collectors and the return air duct is 40 ± 7°F and heating demands are such that direct space heating from the collector array is not required. This mode terminates whenever the differential temperature falls to 25 ± 5°F, or less, or direct space heating from the collector array is required.

2. Collector to Space Heating Load. In this mode dampers MD1 and MD2 are open and solar energy goes directly to the residential area utilizing both the collector and circulating blowers. The DHW heat exchanger is bypassed in this mode and all collected energy is delivered to the space heating load. The same differential temperature conditions described above also control operation in this mode.

3. Storage to Load. When incident solar energy on the collector array is insufficient, space heating is provided from the storage bin by way of the circulating blower. Dampers MD1 and MD3 are closed in this mode and MD2 is open. A minimum storage temperature of 90°F is required for operation in this mode.

B. Second Stage

4. Heat Pump Auxiliary Direct. When insufficient solar energy is present on the collector array and the storage temperature is also insufficient to maintain a level of comfort, dampers MD1 and MD2 close and MD3 opens to provide heated air from the heat pump by way of the auxiliary heating/cooling heat exchanger. At outdoor temperatures of approximately 40°F or above, the heat pump will carry the entire space heating load. For temperatures between 2°F and approximately 40°F, the heat pump is supplemented by the electrical strip heaters.

   It is also possible to heat in this mode while, at the same time, collected solar energy is being delivered to storage. This

condition exists whenever the room thermostat is calling for second stage heating and sufficient insolation is available to allow the collector array to operate.

5. Auxiliary Heat from Heat Pump Storage. This mode allows space heating from the off-peak water storage tank. During off-peak hours, when the heat pump is not needed to heat the residence, it stores hot water for use during this mode. Dampers MD1 and MD2 are closed and MD3 is open in this mode.

C. Third Stage

6. Electrical resistance (strip) heat is used whenever the heat pump is unable to maintain the desired comfort level in the house. Above 2°F the strips supplement the heat pump, as described in Mode 4 above, and below 2°F the strips carry the entire load.

2.1 Typical System Operation

Curves depicting typical system operation on a cold, mostly bright day (February 5, 1979) are presented in Figure 2.1-1. Figure 2.1-1 (a) shows the insolation on the collector array and the period when the array was operating (shaded area). Also shown in Figure 2.1-1 (a) are the collector array temperature profiles. These are the inlet temperature (T100), the outlet temperature (T150) and the absorber plate temperature (T104).

On this particular day the collector array began operating at 0916 hours. At that time the insolation level was 199 Btu/Ft^2-Hr and the absorber plate temperature (T104) was 137°F. At the same time the collector array inlet temperature (T100) was 59°F. This represents a higher differential temperature than the 40 $\pm$ 7°F required between the collector array and return duct to initiate collector array operation. However, it should be noted that T104 and T100 are not control sensors, but only serve to monitor system behavior. These operating temperature constraints are mentioned to make the reader aware that monitoring instrumentation and control sensors have no direct correlation, but monitoring instrumentation can provide sufficient information to determine if each operational mode is functioning within a reasonable range of control temperature sensor limits.

The collector array continued to operate normally throughout the day. It will be noted that T104 tracked the insolation level quite closely during the operational period. The array outlet temperature (T150) also tracked both the insolation level and absorber plate temperature but its fluctuations were not as pronounced as those of the absorber plate temperature. The collector array inlet temperature (T100) showed a gradual rise almost constantly during the operational period. This is expected because the system was operating in the collector to storage and hot water mode most of the day. As a result T100 tended to track the temperature at the bottom of the storage bin fairly closely. The only exception to this occurred at approximately 0937 hours. At that time the system operated

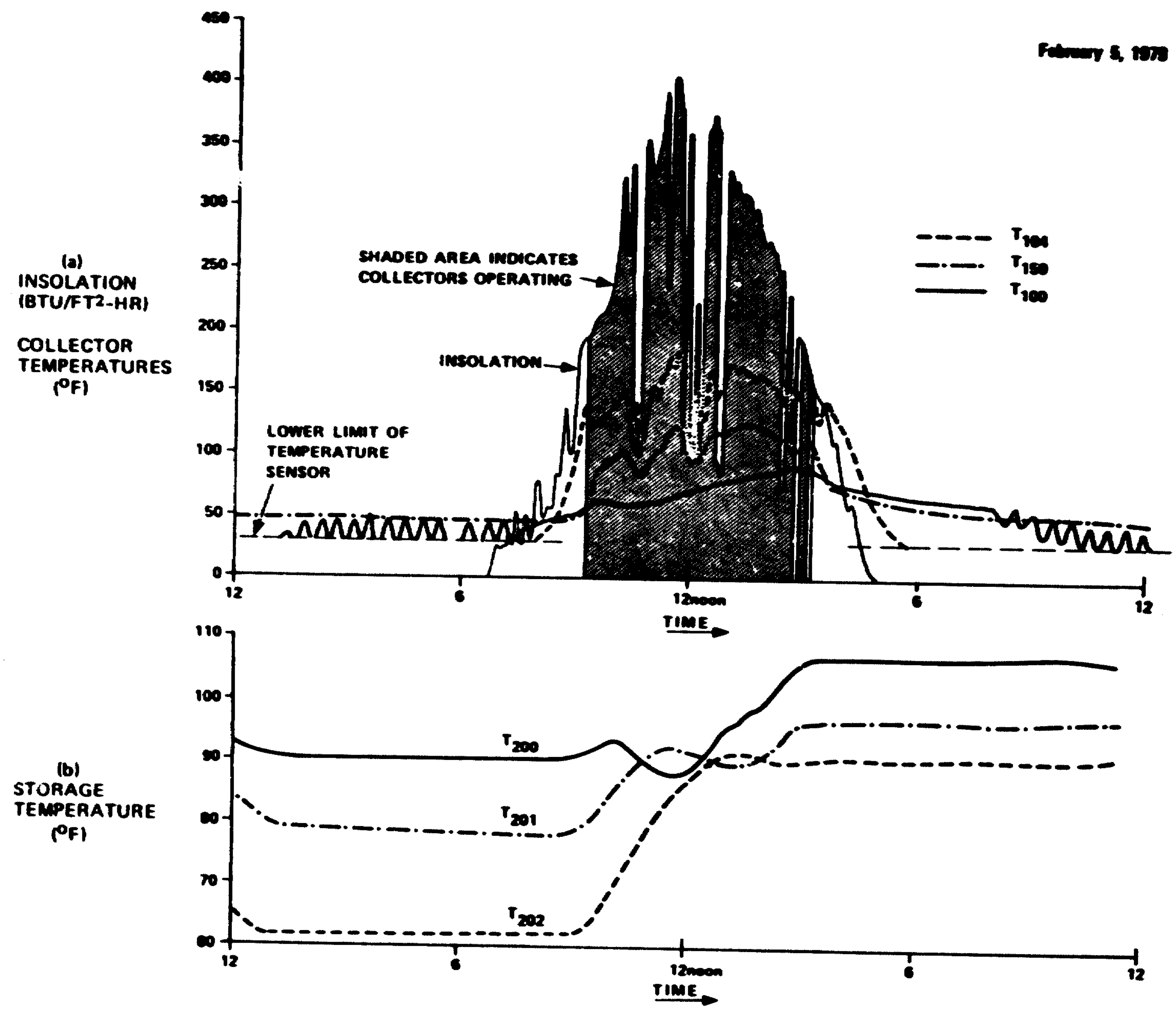

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Figure 2.1-1 Typical System Operating Parameters

briefly (approximately 10 to 15 minutes) in the direct collector to space heating mode. During this time T100 showed a slight decrease, as would be expected.

The collector array continued to operate until 1441 hours when it shut down momentarily for about five minutes. It came back on and ran for approximately 17 minutes until 1503 hours. It cycled on briefly once again at 1508 hours and then shut down for the remainder of the day. Just before the initial shutdown at 1441 hours the array temperature (T104) had dropped approximately 15 degrees (to 126°F) due to a momentary drop in the insolation level. At this time T100 was reading approximately 86°F. This 40°F differential again was greater than the 25 $\pm$ 5°F required to terminate array operation but, as noted before, T104 and T100 do not precisely reflect control sensor temperatures.

Figure 2.1-1 (b) presents a profile of the storage bin temperatures for the selected day. During the first hour the system was providing energy for space heating. However, at 0100 hours the temperature at the top of storage dropped to approximately 90°F and the storage to space heating mode terminated. (It is coincidental that the minimum storage temperature required for space heating is also 90°F). After 0100 hours the system remained in a quiescent state until the collector array began operating and charging storage. During the charging period the temperature profile in the storage bin behaved as would be expected, based on the air flow pattern through the storage bin and the collector array outlet temperature (T150). Once collector array operation, and hence storage charging, ceased, the system remained relatively stable for the rest of the day, as the system did not enter the storage to space heating mode during the evening hours.

2.2 System Operating Sequence

Figure 2.2-1 presents bar charts showing typical system operating sequences for February 5, 1979. This data correlates with the curves presented in Figure 2.1-1 and provides some additional insight into those curves. This particular day was chosen because almost all possible modes of system operation were exercised at some time during the day and, in addition, some system control problems are visibly demonstrated.

There are several interesting observations that can be made relating to the overall space heating subsystem from Figure 2.2-1. First is the poor performance of the auxiliary heating system controls. As can be observed during the first hour of the day, the rock storage bin was providing energy for space heating. However, at the same time the heat pump was attempting to charge the off-peak tank. Normally this would be desirable, but at this particular time the outdoor ambient temperature was below 2°F, so the compressor should not have been running at all. As a result, there was no useful energy gain in the off-peak tank (the temperature remained at approximately 110°F) and the power expended to operate the compressor and pump was wasted. Once the rock storage bin was depleted at approximately 0100 hours, the auxiliary system took over the space heating requirements. However, even though there was some energy available in the off-peak storage tank, the system did not take advantage of it. Instead, the electrical auxiliary heat strips carried the entire heating load. Also during this time period the heat pump system was not working properly. The dashed blocks in Figure 2.2-1 show that the system was trying to operate in the direct heat pump to space heating mode during this period. However, this time the compressor did not come on (the outdoor ambient temperature was now slightly below 0°F) even though the circulating pump (P2) was running. Thus the energy required to operate the pump was wasted. Had the system used the off-peak tank for heating during this time the pump energy expenditure would have been justified and the energy required for the heat strips would have been eliminated or significantly reduced.

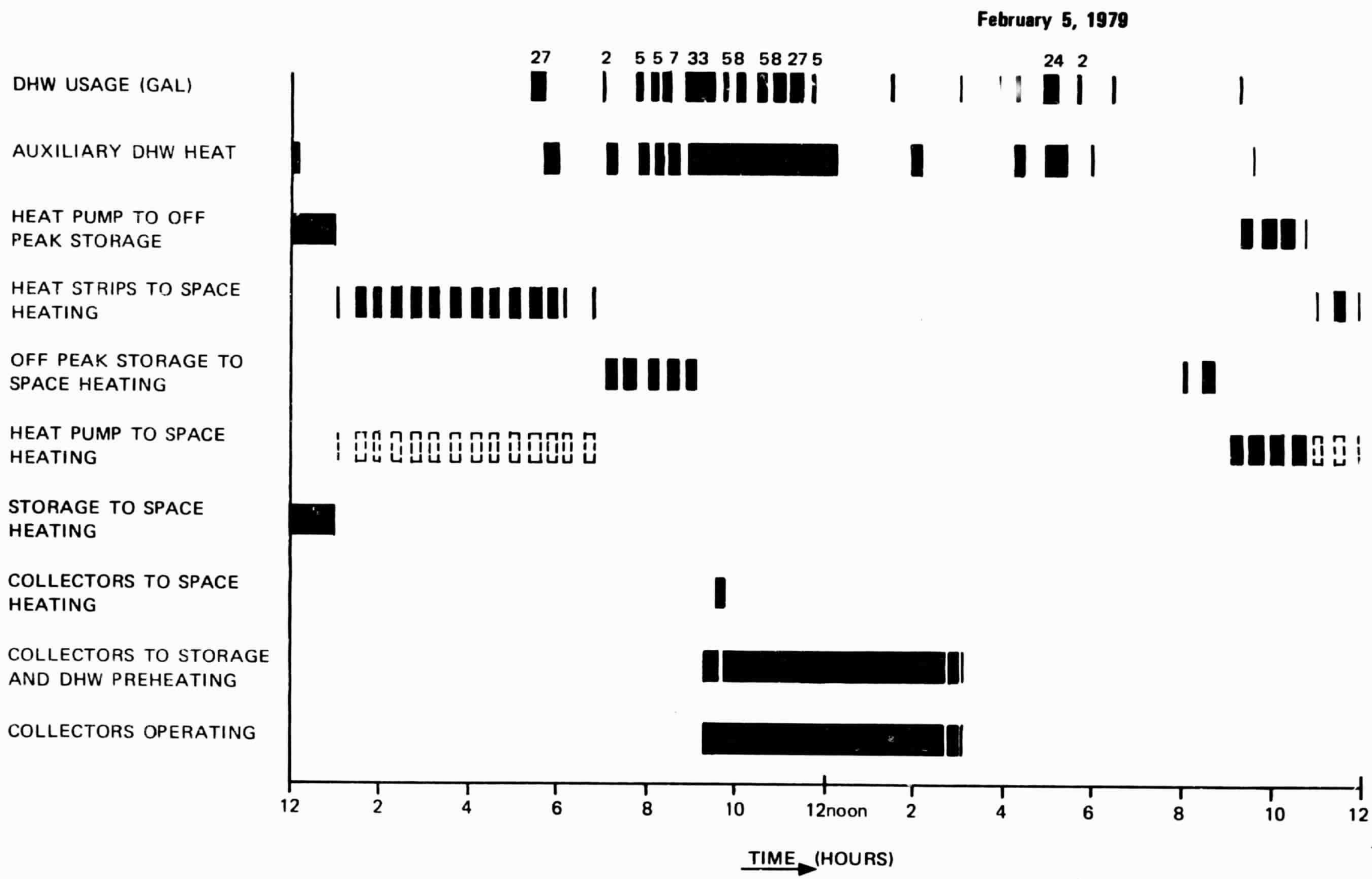

Figure 2.2-1 Typical System Operating Sequence

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At approximately 0700 hours the system began to use the off-peak system for space heating and continued to do so until just after 0900 hours. At this time the solar energy system began operating and there were no further measured space heating demands until the evening. At just after 2000 hours the system again heated from the off-peak storage tank for a brief period of time. Then, beginning shortly after 2100 hours, the heat pump, supplemented by the heat strips, took over the space heating load. This operation continued until approximately 2300 hours and, at this point, unscheduled operation of pump P2 began again.

The second observation to be made concerns the manner in which the space heating demands were satisfied during the evening hours. As noted above they were carried entirely by the auxiliary system, irrespective of the manner in which the auxiliary system was performing. Referring back to Figure 2.1-1, it can be seen that ample solar energy had been delivered to the storage bin during the day to provide a useful space heating contribution during the evening. However, the control system did not initiate the storage to space heating mode at any time during the evening (or during the early morning hours the next day), so the solar energy supplied to storage during the day was not used by the system at night. This also resulted in an unnecessary consumption of electrical auxiliary energy.

The last point to be made relating to the space heating subsystem concerns the lack of any measured heating load during the day when the collector array was operating (except briefly at approximately 0937 hours). With outdoor ambient temperatures below 20°F all day, a substantial heating load would be expected. The problem here has to do with the large amounts of air leakage in the system. This situation is addressed in greater detail later in this report.

Domestic hot water usage for this day was considerably above the 105 gallons per day average for February. As shown in Figure 2.2-1, approximately 170 gallons of water was used during the day (bars without a value above them represent usages of less than 2 gallons). Therefore, a higher than normal amount of auxiliary energy was required to support the DHW subsystem.

3. PERFORMANCE ASSESSMENT

The performance of the Solaron Akron Solar Energy System has been evaluated for the November 1978 through October 1979 time period from two perspectives. The first was the overall system view in which the performance values of system solar fraction and net energy savings were evaluated against the prevailing and long-term average climatic conditions and system loads. The second view presents a more in-depth look at the performance of the individual subsystems. Details relating to the performance of the system are presented first in Section 3.1 followed by the subsystem assessment in Section 3.2.

For the purposes of this Solar Energy System Performance Evaluation, monthly performance data were regenerated to reflect refinements and improvements in the system performance equations that were incorporated as the analysis period progressed. These modifications resulted in changes in the numerical values of some of the performance factors. However, the basic trends have not been affected.

Before beginning the discussion of actual solar energy system performance some highlights and pertinent information relating to site history are presented in the following paragraphs.

The Solaron Akron Solar Energy System was initially activated in August 1978. At that time all known system problems were addressed and corrected where possible. After the system was started up, a period of data monitoring was initiated to verify that the solar system and monitoring instrumentation were functioning properly.

During the initial check-out phase there were several problems identified relating to both the solar energy system and the monitoring instrumentation.

Some of the more significant problems were: six temperature probe thermowells were too short; the bypass line to the hot water tempering valve was located incorrectly with respect to the hot water totalizing flowmeter (W302); the supply water temperature sensor (T302) was reading high due to being located too close to other elements in the hot water subsystem; the collector loop operation was somewhat erratic; and a significant amount of collector array leakage was observed.

These problems, with the exception of the collector array leakage, were all corrected before the system entered the reporting phase in November 1978. The collector array leakage problem was accepted because it would have been very difficult (and costly) to correct it. Also, T302 was damaged when it was relocated to a point further away from the hot water subsystem, and W400 failed in October. Software modifications were incorporated to provide a temporary solution to these last two problems until a site visit could be made in December to correct them.

Once the system entered the reporting period there were very few additional instrumentation problems noted. However, control problems, especially with the off-peak heating (and cooling) system, were noted throughout the reporting period. These problems, where applicable, have been addressed in the appropriate subsections.

3.1 System Performance

This Seasonal Report provides a system performance evaluation summary of the operation of the Solaron Akron Solar Energy System located in Akron, Ohio. This analysis was conducted by evaluation of measured system performance against the expected performance with long-term average climatic conditions. The performance of the system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report, "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [3]. The performance of the major subsystems is also evaluated in subsequent sections of this report.

The measurement data were collected for the period November 1978 through October 1979. System performance data were provided through an IBM developed Central Data Processing System (CDPS) [4] consisting of a remote Site Data Acquisition System (SDAS), telephone data transmission lines and couplers, an IBM System 7 computer for data management, and an IBM System 370/145 computer for data processing. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. These data are processed daily and summarized into monthly performance formats which form a common basis for comparative system evaluation. These monthly summaries are the basis of the evaluation and data given in this report.

The solar energy system performance summarized in this section can be viewed as the dependent response of the system to certain primary inputs. This relationship is illustrated in Figure 3.1-1. The primary inputs are the incident solar energy, the outdoor ambient temperature and the system load. The dependent responses of the system are the system solar fraction and the total energy savings. Both the input and output definitions are as follows:

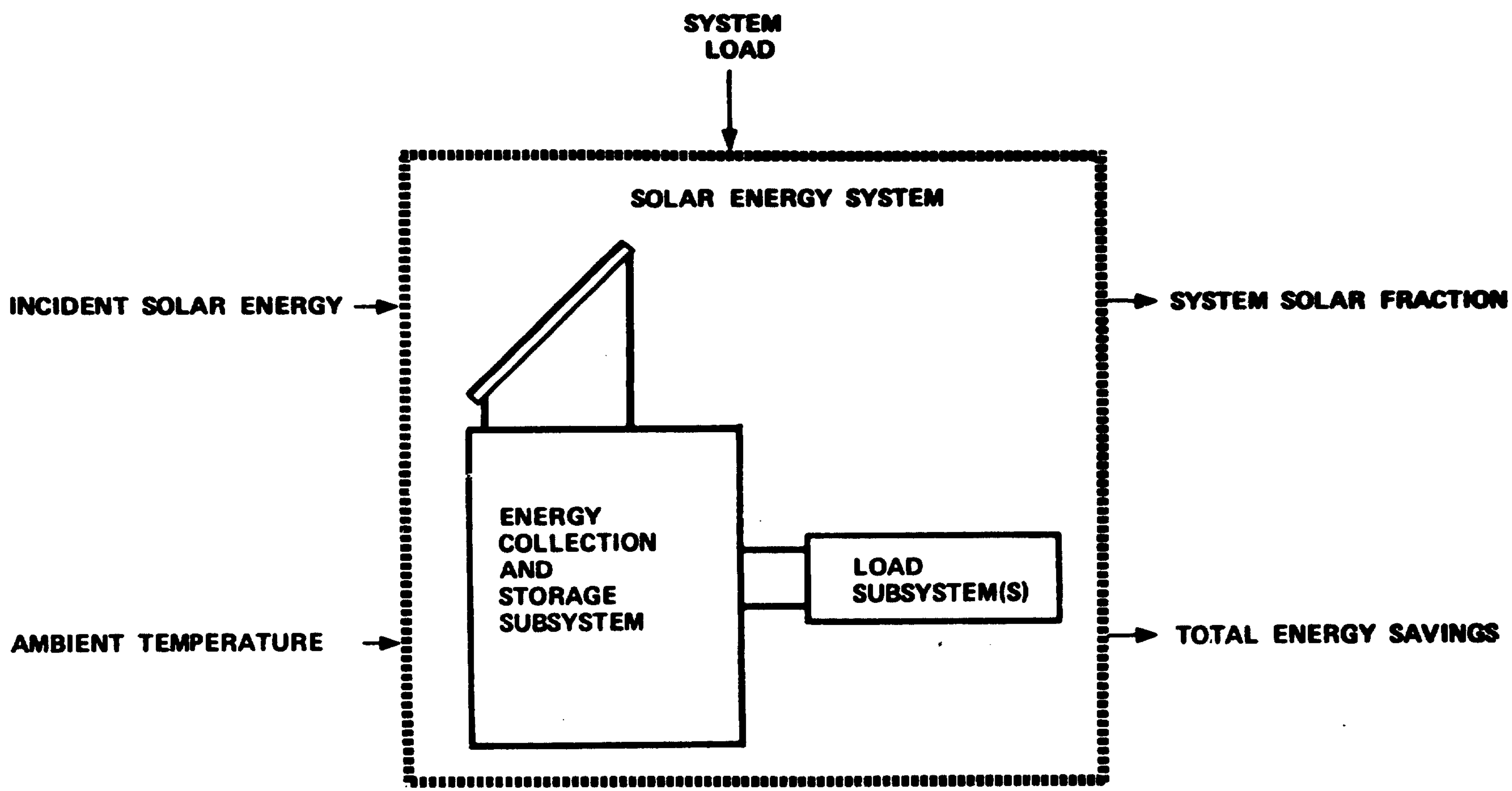


Figure 3.1.1 Solar Energy System Evaluation Block Diagram

Inputs

- Incident solar energy - The total solar energy incident on the collector array and available for collection.

- Ambient temperature - The temperature of the external environment which affects both the energy that can be collected and the energy demand.

- System load - The loads that the system is designed to meet, which are affected by the life style of the user (space heating/cooling, domestic hot water, etc., as applicable).

Outputs

- System solar fraction - The ratio of solar energy applied to the system loads to total energy (solar plus auxiliary energy) required by the loads.

- Total energy savings - The quantity of auxiliary energy (electrical or fossil) displaced by solar energy.

The monthly values of the inputs and outputs for the total operational period are shown in Table 3.1-1, the System Performance Summary. Comparative long-term average values of daily incident solar energy and outdoor ambient temperature are given for reference purposes. The long-term data are taken from Reference 1 of Appendix C. Generally the solar energy system is designed to supply an amount of energy that results in a desired value of system solar fraction while operating under climatic conditions that are defined by the long-term average value of daily incident solar energy and outdoor ambient temperature. If the actual

TABLE 3.1-1

SYSTEM PERFORMANCE SUMMARY

SOLARON AKRON

Month	Daily Incident Solar Energy Per Unit Area (45° Tilt) (Btu/Ft^2-Day)		Ambient Temperature (°F)		System Load - Measured (Million Btu)	Solar Fraction (Percent)		Total Energy Savings (Million Btu)
	Measured	Long-Term Average	Measured	Long-Term Average		Measured	Expected	
Nov 78	791	794	43	41	2.72	18	9	0.26
Dec 78	677	570	32	29	4.61	19	9	0.70
Jan 79	590	681	21	26	7.21	9	5	0.56
Feb 79	1,069	905	19	28	6.36	17	12	0.90
Mar 79	1,198	1,143	42	36	3.02	46	26	1.13
Apr 79	1,130	1,353	47	49	2.48*	37*	30	0.85*
May 79	1,376	1,460	58	59	2.05	16	25	0.22
Jun 79	1,486	1,518	68	68	1.37	39	54	0.41
Jul 79	1,514	1,515	71	72	1.48	39	57	0.44
Aug 79	1,257	1,510	69	70	1.39	40	59	0.45
Sep 79	1,486	1,435	64	64	1.31	55	54	0.57
Oct 79	841	1,266	51	53	1.59	33	27	0.39
Total	--	--	--	--	35.59	--	--	6.88
Average	1,118	1,179	49	50	2.97	24 **	22	0.57

*The DHW flowmeter (W302) was defective during April. Therefore the DHW subsystem contribution to these overall system parameters is based on appropriate DHW subsystem averages.

**Average is weighted by the measured system load.

climatic conditions are close to the long-term average values, there is little adverse impact on the system's ability to meet design goals. This is an important factor in evaluating system performance and is the reason the long-term average values are given. The data reported in the following paragraphs are taken from Table 3.1-1.

At the Solaron Akron site for the 12 month report period, the long-term average daily incident solar energy in the plane of the collector array was 1,179 Btu/Ft^2. The average daily measured value was 1,118 Btu/Ft^2, which is about five percent below the long-term value. On a monthly basis, October of 1979 was the worst month with an average daily measured value of incident solar energy 34 percent below the long-term average daily value. December 1978 was the best month with an average daily measured value 19 percent above the long-term average daily value. On a long-term basis it is obvious that the good and bad months almost average out so that the long-term average performance should not be adversely influenced by small differences between measured and long-term average incident solar energy. It should be noted that monthly performance assessments prior to September 1979 for this site provided long-term reference insolation data based on averages measured in the horizontal plane, rather than the plane of the collector array. As a result, they would be somewhat low when compared to insolation in the plane of the collector array. As noted above the values in Table 3.1-1 are all in the plane of the collector array.

The outdoor ambient temperature influences the operation of the solar energy system in two important ways. First the operating point of the collectors and consequently the collector efficiency or energy gain is determined by the difference in the outdoor ambient temperature and the collector inlet temperature. This will be discussed in greater detail in Section 3.2.1. Secondly the load is influenced by the outdoor ambient temperature. The long-term average daily ambient temperature for the 12 month period from November 1978 through October 1979 was 50°F at the Solaron Akron site. This compares very favorably with the measured value of 49°F.

It is interesting to note the strong influence that the local weather conditions had on the measured solar fraction. For example, the measured average outdoor ambient temperature in January 1979 was 21°F (five degrees below the long-term average), and in February 1979 it was 19°F (nine degrees below the long-term average). Thus, the average outdoor ambient temperature was quite close for these two months. In January the measured insolation was 13 percent below the long-term average and the measured solar fraction was nine percent. However, in February the measured insolation was 18 percent above the long-term average and the measured solar fraction was 17 percent. In March 1979 the measured insolation was five percent above the long-term average, and the measured average outdoor ambient temperature of 42°F was six degrees above the long term average. The measured solar fraction increased markedly to 46 percent for that month. These observations serve to reinforce the earlier statement concerning the impact of prevailing weather conditions on the performance of a solar energy system.

The system load has an important affect on the system solar fraction and the total energy savings. If the load is small and sufficient energy is available from the collectors, the system solar fraction can be expected to be large. However, the total energy savings will be less than under more nominal load conditions. This is illustrated by comparing the performance of the system during the summer (June, July and August) and winter (December, January and February) months. During the summer the space heating load was negligible and the system was used primarily to support the hot water load. As a result the system solar fraction was approximately three times higher than during the winter months. However, the total measured savings during the winter were almost twice as high as during the summer and the measured winter load was over four times greater than the summer load.

Also presented in Table 3.1-1 are the measured and expected values of system solar fraction where system solar fraction is the ratio of solar energy applied to system loads to the total energy (solar plus auxiliary) applied to the loads. The expected values have been derived from a modified f-Chart analysis which uses measured weather and subsystem loads as inputs (f-Chart is the designation of a procedure that was developed by the Solar Energy Laboratory, University of Wisconsin, Madison, for modeling and designing solar energy systems [8]). The model used in the analysis is based on manufacturers' data and other known system parameters. The basis for the model is a set of empirical correlations developed for liquid and air solar energy systems that are presented in graphical and equation form and referred to as the f-Charts, where 'f' is a designator for the system solar fraction. The output of the f-Chart procedure is the expected system solar fraction. The measured value of system solar fraction was computed from measurements, obtained through the instrumentation system, of the energy transfers that took place within the solar energy system. These represent the actual performance of the system installed at the site.

The measured value of system solar fraction can generally be compared with the expected value so long as the assumptions which are implicit in the f-Chart procedure reasonably apply to the system being analyzed. As shown in Table 3.1-1, the measured system solar fraction of 24 percent compared well with the expected value of 22 percent generated by the modified f-Chart program. However, even though the yearly values of the measured and predicted system solar fraction compared closely, there was a considerable difference between the individual monthly values. The exact reason for this disparity is not known, but there are several factors that should be considered. First it will be noted that the expected solar fraction averaged 56 percent during the summer months, as opposed to a measured average of 43 percent. During this time period there was a control problem that resulted in cyclic operation of the

collector array and hot water recirculation pump. This resulted in less efficient operation of the hot water subsystem and hence served to reduce performance. Also during the summer months the system flow path is changed. Dampers D1 and D2 are adjusted so that air flow does not circulate through storage. In this configuration the collector array performance is reduced because the inlet temperature to the array will be considerably higher than when the full system is being utilized. It is suspected that this also has a bearing on expected versus actual system solar fraction.

During the remaining eight months of the year the expected solar fraction was generally lower than the measured solar fraction. Again, however, there are several unusual circumstances that tend to cloud the picture. First of all it should be noted that there is no flowmeter in the immediate vicinity of the storage bin and, in addition, the collector array itself leaks a substantial amount. As a result it is difficult to get an accurate representation of system air flow in the collector to storage mode of operation. This parameter is needed to compute one of the inputs for the f-Chart model. Also, the system exhibits a considerable amount of internal air leakage and this problem also tends to affect the computations. To further compound the difficulties the air flow correction factors for the first five months (November through March) were not firmly established. This caused additional inaccuracies in air flow measurements throughout the system. Finally, it must be remembered that in April the hot water subsystem contribution to the total system solar fraction was based on estimated, rather than actual data.

Based on all the foregoing problems, a great deal of reliance cannot be placed in the short term f-Chart predictions and comparisons for this solar energy system. However, based on the long-term results, the utility of this analysis tool should not be underestimated.

The total energy savings is the most important performance parameter for the solar energy system because the fundamental purpose of the system is to replace expensive conventional energy sources with inexpensive solar energy. In practical consideration, the system must save enough energy to cover both the cost of its own operation and to repay the initial investment for the system. In terms of the technical analysis presented in this report the net total energy savings should be a significant positive figure. The total computed energy savings for the Solaron Akron Solar Energy System was 6.88 million Btu, or 2,015 kwh, which was not a large amount of energy. However, this savings is based only on measured inputs of solar energy to the load subsystems. At the Solaron Akron site there were a significant amount of uncontrolled (and hence unmeasured) inputs of solar energy into the house. These uncontrolled inputs of solar energy came primarily from storage and transport losses and tended to reduce the overall heating load, which in turn tended to increase real savings. This situation is addressed in more detail in the appropriate sections that follow.

3.2 Subsystem Performance

The Solaron Akron Solar Energy Installation may be divided into four subsystems:

1. Collector array
2. Storage
3. Hot water
4. Space heating

Each subsystem has been evaluated by the techniques defined in Section 3 and is numerically analyzed each month for the monthly performance assessment. This section presents the results of integrating the monthly data available on the four subsystems for the period November 1978 through October 1979.

3.2.1 Collector Array Subsystem

The Solaron Akron collector array consists of 28 Solaron 2000 series flat-plate air collectors arranged in two parallel rows of 14 collectors each. These collectors are a one-pass air heating type with a double glazing. Typical flowrate through the collector array is approximately 1.85 CFM per square foot of gross array area. Details of the air flow path are shown in Figure 3.2.1-1 (a) and a photograph of the collector array installation is presented in Figure 3.2.1-1 (b). The collector subsystem analysis and data are given in the following paragraphs.

Collector array performance is described by the collector array efficiency. This is the ratio of collected solar energy to incident solar energy, a value always less than unity because of collector losses. The incident solar energy may be viewed from two perspectives. The first assumes that all available solar energy incident on the collectors must be used in determining collector array efficiency. The efficiency is then expressed by the equation:

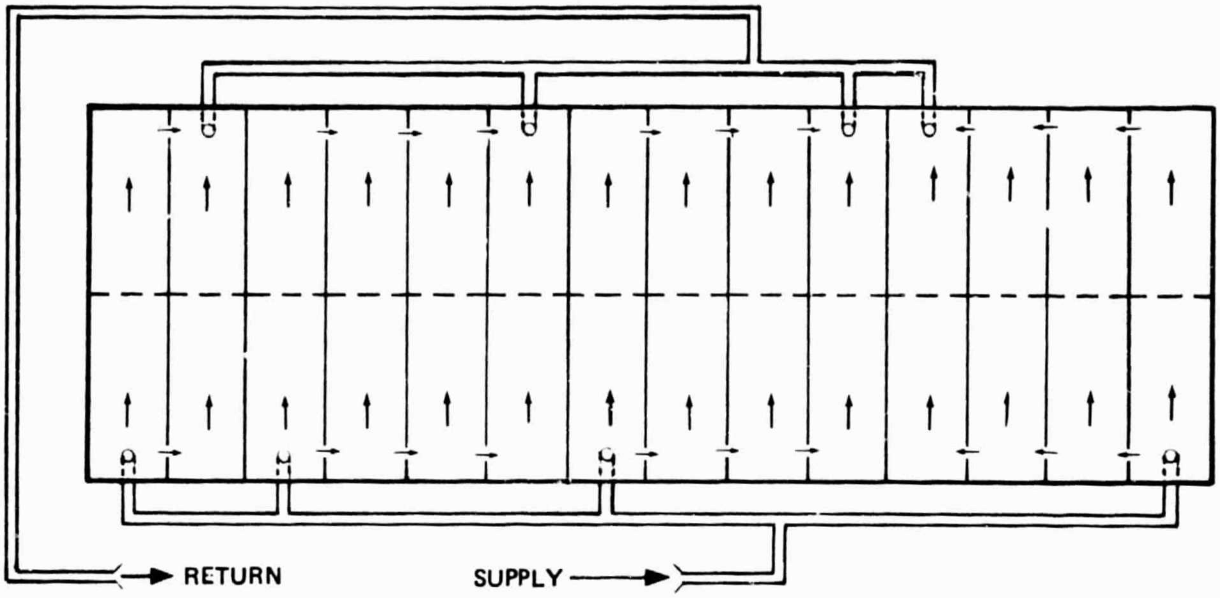
$$\eta_c = Q_s/Q_i \tag{1}$$

where η_c = Collector array efficiency

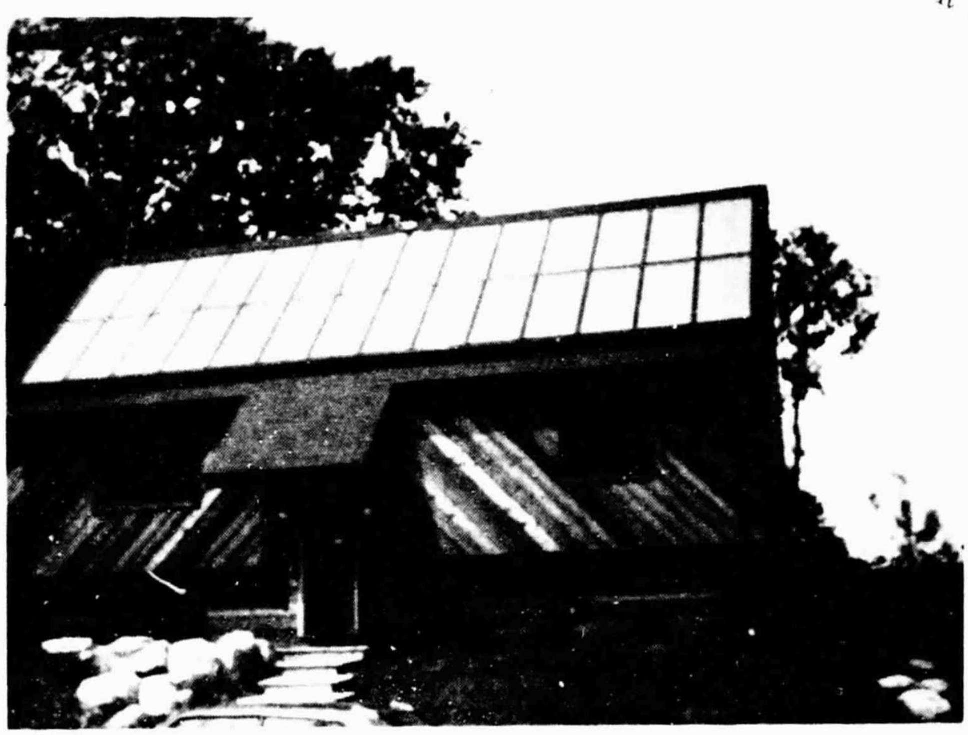
Q_s = Collected solar energy

Q_i = Incident solar energy

The efficiency determined in this manner includes the operation of the control system. For example, solar energy can be available at the collector, but the collector absorber plate temperature may be below the minimum control temperature set point for collector loop operation, thus the energy is not collected. The monthly efficiency by this method is listed in the column entitled "Collector Array Efficiency" in Table 3.2.1-1.



(a) Collector Air Flow Path



(b) Collector Array Installation

COLLECTOR ARRAY		SITE LOCATION	
Tilt Angle	– 45^{o}	Latitude	– 40.92^{o}N
Azimuth	– Due South	Longitude	– 81.43^{o}W

Figure 3.2.1-1 Collector Details

The second viewpoint assumes that only the solar energy incident on the collector when the collector loop is operational be used in determining the collector array efficiency. The value of the operational incident solar energy used is multiplied by the ratio of the gross collector area to the gross collector array area to compensate for the difference between the two areas caused by installation spacing. The efficiency is then expressed by the equation:

$$\eta_{co} = Q_s/(Q_{oi} \times A_p/A_a) \qquad (2)$$

where η_{co} = Operational collector array efficiency

Q_s = Collected solar energy

Q_{oi} = Operational incident solar energy

A_p = Gross collector area (the product of the number of collectors and the envelope area of one collector)

A_a = Gross collector array area (total area including all mounting and connecting hardware and spacing of units)

The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency" in Table 3.2.1-1.

It should be noted that the values for collected solar energy and both collector array efficiency terms presented in Table 3.2.1-1 are somewhat suspect for the first five months (November 1978 through March 1979). This is due to the fact that the air flow correction factors were not firmly established for these months. Based on data for the remaining seven months in the report period and additional information from site operation obtained after the close of the formal data assessment period, the reported values for the first five months are probably thirty percent higher than they actually were.

TABLE 3.2.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Array Efficiency
Nov 78*	12.96	4.08	0.31	8.51	0.50
Dec 78*	11.46	3.52	0.31	6.54	0.54
Jan 79*	9.99	2.08	0.21	4.13	0.50
Feb 79*	16.34	5.50	0.34	9.42	0.58
Mar 79*	20.27	6.88	0.34	11.67	0.59
Apr 79	18.51	4.24	0.23	11.54	0.37
May 79**	23.28	1.99	0.09	6.05	0.33
Jun 79	24.34	2.08	0.09	9.37	0.22
Jul 79	25.63	2.13	0.08	9.11	0.23
Aug 79	21.27	1.78	0.08	7.65	0.23
Sep 79	24.34	3.70	0.15	12.80	0.29
Oct 79	14.24	2.80	0.20	7.99	0.35
Total	222.63	40.78	--	104.42	--
Average	18.55	3.40	0.18	8.70	0.39

* Collected solar energy and collector efficiencies appear to be high. See last paragraph on page 26 for for explanation.

**The collector array did not operate from May 11 to May 30 due to a control problem.

In the ASHRAE Standard 93-77 [5] a collector efficiency is defined in the same terminology as the operational collector array efficiency. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector array efficiency is determined from actual dynamic conditions of daily solar energy system operation in the field.

The ASHRAE Standard 93-77 definitions and methods often are adopted by collector manufacturers and independent testing laboratories in evaluating the collectors. The collector evaluation performed for this report using the field data indicates that there was some difference between the laboratory single panel collector data and the collector data determined from long-term field measurements. This may or may not always be the case, and there are two primary reasons for differences when they exist:

- Test conditions are not the same as conditions in the field, nor do they represent the wide dynamic range of field operation (i.e. inlet and outlet temperature, flow rates and flow distribution of the heat transfer fluid, insolation levels, aspect angle, wind conditions, etc.).

- Collector tests are not generally conducted with units that have undergone the effects of aging (i.e. changes in the characteristics of the glazing material, collection of dust, soot, pollen or other foreign material on the glazing, deterioration of the absorber plate surface treatment, etc.).

Consequently field data collected over an extended period will generally provide an improved source of collector performance characteristics for use in long-term system performance definition.

The long-term data base for Solaron Akron includes all but two of the months from April 1979 through February 1980. Although the system was operating prior to April 1979, there were problems relating to the accuracy of air flow correction factors during the initial five months of the reporting period. Therefore, data obtained prior to April 1979 have not been included in the data base. However, site data was collected and archived beyond the end of the formal data assessment period. This additional data was used to build the long-term data base for the collector array analysis. A four month extension of the long-term data base enabled the generation of a more accurate assessment of collector array performance.

July and December are not included in the long-term data base. In July data was lost for 17 days, and in December the filtered collector array performance data exhibited too much scatter to be usable.

The operational collector array efficiency data given in Table 3.2.1-1 are monthly averages based on instantaneous efficiency computations over the total performance period using all available data. For detailed collector analysis it was desirable to use a limited subset of the available data that characterized collector operation under "steady state" conditions. This subset was defined by applying the following restrictions:

(1) The measurement period was restricted to collector operation when the sun angle was within 30 degrees of the collector normal.

(2) Only measurements associated with positive energy gain from the collectors were used, i.e., outlet temperatures must have exceeded inlet temperatures.

(3) The sets of measured parameters were restricted to those where the rate of change of all parameters of interest during two regular data system intervals* was limited to a maximum of 5 percent.

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*The data system interval was 5-1/3 minutes in duration. Values of all measured parameters were continuously sampled at this rate throughout the performance period.

Instantaneous efficiencies (η_j) computed from the "steady state" operation measurements of incident solar energy and collected solar energy by Equation (2)* were correlated with an operating point determined by the equation:

$$x_j = \frac{T_i - T_a}{I} \tag{3}$$

where x_j = Collector operating point at the j^{th} instant

T_i = Collector inlet fluid temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

The data points (η_j, x_j) were then plotted on a graph of efficiency versus operating point and a first order curve described by the slope-intercept formula was fitted to the data through linear regression techniques. The form of this fitted efficiency curve is:

$$\eta_j = b - mx_j \tag{4}$$

where η_j = Collector efficiency corresponding to the j^{th} instant

b = Intercept on the efficiency axis

$(-)m$ = Slope

x_j = Collector operating point at j^{th} instant

The relationship between the empirically determined efficiency curve and the analytically developed curve will be established in subsequent paragraphs.

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*The ratio A_p/A_a is assumed to be unity for this analysis.

The analytically developed collector efficiency curve is based on the Hottell-Whillier-Bliss equation

$$\eta = F_R(\tau\alpha) - F_R U_L \left(\frac{T_i - T_a}{I} \right) \qquad (5)$$

where η = Collector efficiency

F_R = Collector heat removal factor

τ = Transmissivity of collector glazing

α = Absorptance of collector plate

U_L = Overall collector energy loss coefficient

T_i = Collector inlet fluid temperature

T_a = Outdoor ambient temperature

I = Rate of incident solar radiation

The correspondence between equations (4) and (5) can be readily seen. Therefore by determining the slope-intercept efficiency equation from measurement data, the collector performance parameters corresponding to the laboratory single panel data can be derived according to the following set of relationships:

$$b = F_R(\tau\alpha) \qquad (6)$$

and

$$m = F_R U_L$$

where the terms are as previously defined

The discussion of the collector array efficiency curves in subsequent paragraphs is based upon the relationships expressed by Equation (6).

In deriving the collector array efficiency curves by the linear regression technique, measurement data over the entire performance period yields higher confidence in the results than similar analysis over shorter periods. Over the longer periods the collector array is forced to operate over a wider dynamic range. This eliminates the tendency shown by some types of solar energy systems to cluster efficiency values over a narrow range of operating points. The clustering effect tends to make the linear regression technique approach constructing a line through a single data point. The use of data from the entire performance period results in a collector array efficiency curve that is more accurate in long-term solar system performance prediction. The long-term curve and the curve derived from the laboratory single panel data are shown in Figure 3.2.1-2.

The long-term first order curve presented in Figure 3.2.1-2 indicates that the collector array as a whole seemed to perform better than the laboratory test unit. However, this is probably due to the fact that the performance equations for the collector array take into account the leakage of outside ambient air into the array. Also the long-term first order curve has a slightly less negative slope than the curve derived from single panel laboratory test data. This is attributable to lower losses (other than leakage) resulting from array effects. The laboratory predicted instantaneous efficiency is not in close agreement with the curve derived from actual field operation. This indicates that the laboratory derived curve might not be useful for design purposes in an array configuration of this type. However, this statement must be tempered by the fact that actual performance might approach predicted performance more closely if there were no leakage problems with the collector array or ductwork.

For information purposes the data associated with Figure 3.2.1-2 is as follows:

Single panel laboratory data

$F_R(\tau\alpha) = 0.476$ $\qquad$ $F_R U_L = -0.856$

Long-term field data

$F_R(\tau\alpha) = 0.507$ $\qquad$ $F_R U_L = -0.649$

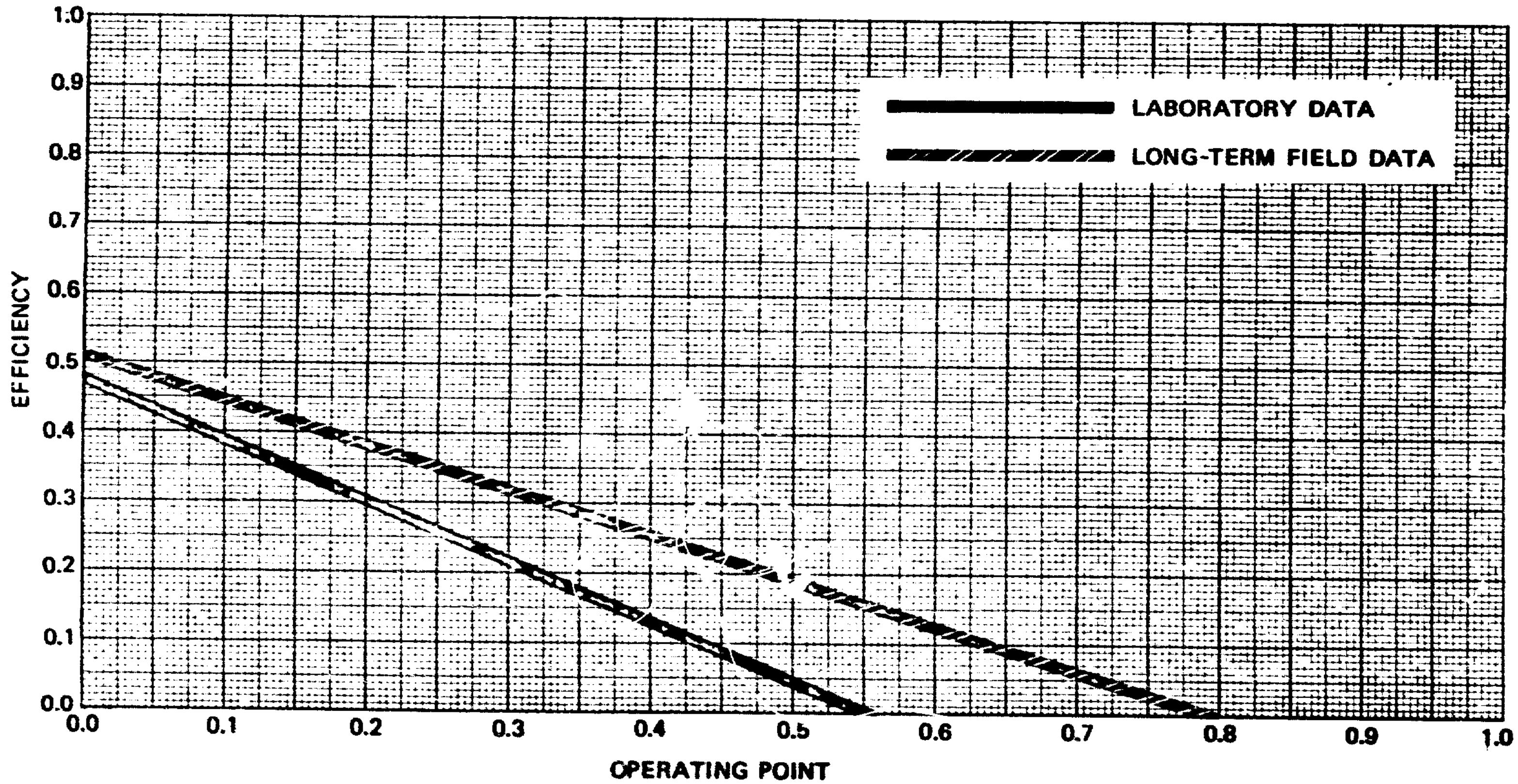

Figure 3.2.1-2 Solaron Akron Collector Efficiency Curves

Table 3.2.1-2 presents data comparing the monthly measured values of solar energy collected with the predicted performance determined from the long-term regression curve and the laboratory single panel efficiency curve. The predictions were derived by the following procedure:

1. The instantaneous operating points were computed using Equation (3).

2. The instantaneous efficiency was computed using Equation (4) with the operating point computed in Step 1 above for:

   a. The long-term linear regression curve for collector array efficiency

   b. The laboratory single panel collector efficiency curve

3. The efficiencies computed in Steps 2a and 2b above were multiplied by the measured solar energy available when the collectors were operational to give two predicted values of solar energy collected.

The error data in Table 3.2.1-2 were computed from the differences between the measured and predicted values of solar energy collected according to the equation:

$$\text{Error} = (A-P)/P \tag{7}$$

where A = Measured solar energy collected
P = Predicted solar energy collected

The computed error is then an indication of how well the particular prediction curve fitted the reality of dynamic operating conditions in the field.

TABLE 3.2.1-2

ENERGY GAIN COMPARISON

(ANNUAL)

SITE: SOLARON AKRON AKRON, OHIO

Month	Collected Solar Energy (Million Btu)	Error	
		Field Derived Long Term	Laboratory Single Panel
Apr 79	4.221	-0.064	0.253
May 79	1.988	-0.079	0.231
Jun 79	1.934	-0.184	0.255
Aug 79	1.914	-0.170	0.205
Sep 79	3.905	-0.092	0.202
Oct 79	2.781	-0.057	0.179
Nov 79	2.462	-0.052	0.229
Jan 80	2.351	0.019	0.302
Feb 80	3.410	0.067	0.380
Average	2.774	-0.059	0.251

The values of "Collected Solar Energy" given in Table 3.2.1-2 are not necessarily identical with the values of "Collected Solar Energy" given in Table 3.2.1-1. Any variations are due either to differences in the data base or to the differences in data processing between the software programs used to generate the monthly performance assessment data and the component level collector analysis program. These data are shown in Table 3.2.1-2 only because they form the references from which the error data given in the table are computed.

The data from Table 3.2.1-2 illustrates that, for the Solaron Akron site, the average error computed from the difference between the measured solar energy collected and the predicted solar energy collected based on the field derived long-term collector array efficiency curve was -5.9 percent. For the curve derived from the laboratory single panel data, the error was 25.1 percent. Thus the long-term collector array efficiency curve gives significantly better results than the laboratory single panel curve.

A histogram of collector array operating points illustrates the distribution of instantaneous values as determined by Equation (3) for the entire month. The histogram was constructed by computing the instantaneous operating point value from site instrumentation measurements at the regular data system intervals throughout the month, and counting the number of values within contiguous intervals of width 0.01 from zero to unity. The operating point histogram shows the dynamic range of collector operation during the month from which the midpoint can be ascertained. The average collector array efficiency for the month can then be derived by projecting the midpoint value to the appropriate efficiency curve and reading the corresponding value of efficiency.

Another characteristic of the operating point histogram is the shifting of the distribution along the operating point axis. This can be explained in terms of the characteristics of the system, the climatic factors

of the site, i.e., incident solar energy and ambient temperature, and the method of system operation. Figure 3.2.1-3 shows two histograms that illustrate a typical winter month (February) and a typical summer month (August) operation. The approximate average operating point for February is at 0.22 and for August at 0.29. In terms of Equation (3) it can be seen that, as the operating point becomes larger, the collector array efficiency decreases. At the Solaron Akron site it will be recalled that the flow path is changed during the summer months so that air circulates in a tight path between the outlet and inlet of the collector array. The only mechanisms for extracting energy in this flow configuration are the DHW heat exchanger and duct losses. As a result, the collector array inlet temperature becomes very high and the collector array efficiency tends to decrease, even though both the insolation level and the outside ambient temperature also tend to increase in the summer months. The behavior is further illustrated by considering the data in Table 3.2.1-1.

Table 3.2.1-1 presents the monthly values of incident solar energy, operational incident solar energy, and collected solar energy from the 12 month performance period. The collector array efficiency and operational collector array efficiency were computed for each month using Equations (1) and (2). On the average the operational collector array efficiency exceeded the collector array efficiency, which included the effect of the control system, by 117 percent.

Additional information concerning collector array analysis in general may be found in Reference [7]. The material in the reference describes the detailed collector array analysis procedures and presents the results of analyses performed on numerous collector array installations across the United States.

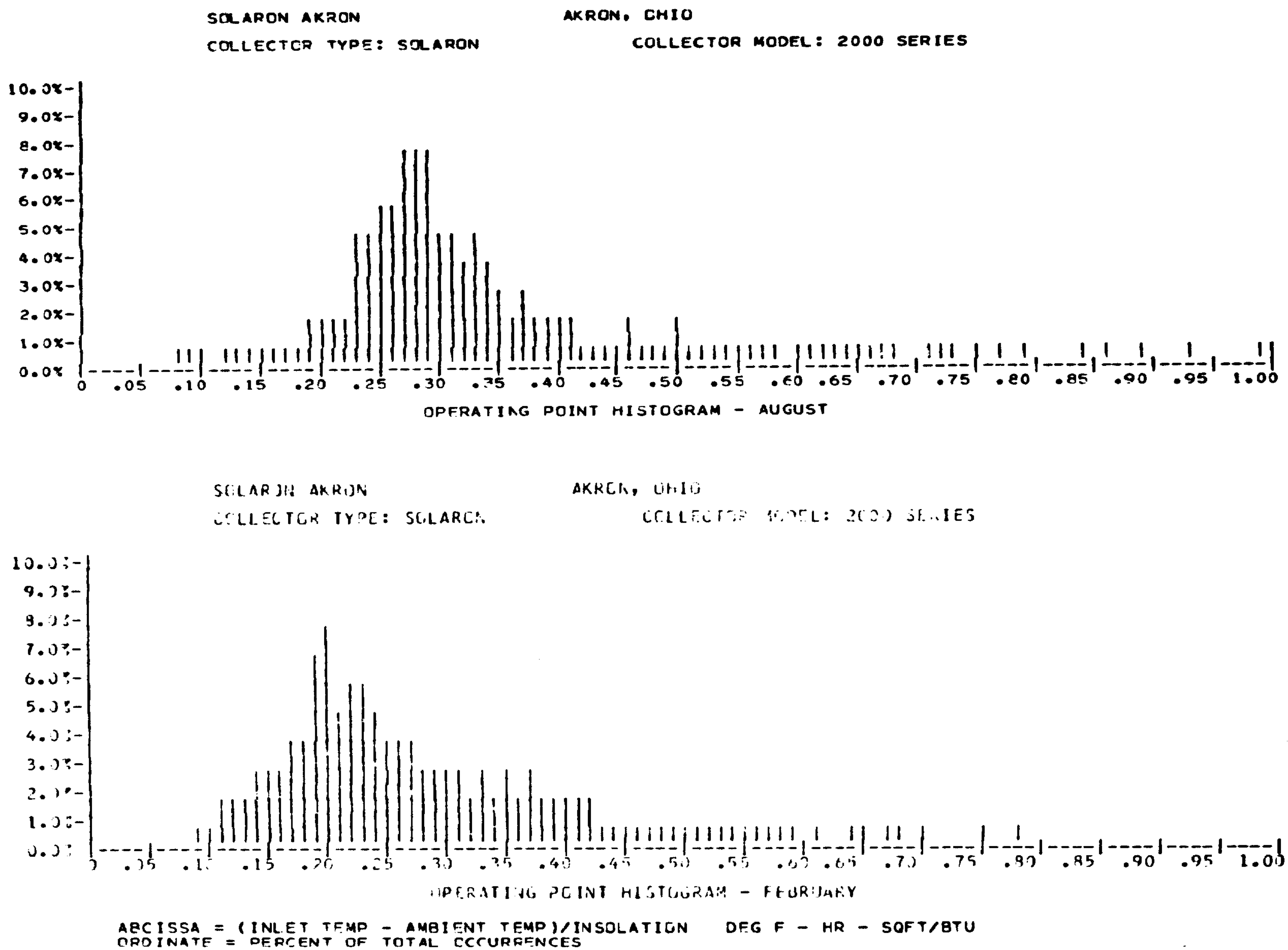

Figure 3.2.1-3 Solaron Akron Operating Point Histograms for Typical Winter and Summer Months

3.2.2 Storage Subsystem

Storage subsystem performance is described by comparison of energy to storage, energy from storage and change in stored energy. The ratio of the sum of energy from storage and change in stored energy to energy to storage is defined as storage efficiency, η_s. This relationship is expressed in the equation

$$\eta_s = (\Delta Q + Q_{so})/Q_{si} \qquad (8)$$

where:

ΔQ = Change in stored energy. This is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value)

Q_{so} = Energy from storage. This is the amount of energy extracted by the load subsystem from the primary storage medium

Q_{si} = Energy to storage. This is the amount of energy (both solar and auxiliary) delivered to the primary storage medium

Evaluation of the system storage performance under actual system operation and weather conditions can be performed using the parameters defined above. The utility of these measured data in evaluation of the overall storage design can be illustrated in the following discussion.

Table 3.2.2-1 summarizes the storage subsystem performance during the report period. However, before discussing storage subsystem performance it is necessary to point out a minor difficulty relating to the monitoring instrumentation in the storage loop. Examination of Figure 2-1 will reveal that there is no flowmeter in the ducts leading directly in or out of the storage bin. Physical limitations prevented the installation of a flowmeter in this area, so other flowmeters (W100, W101 and W600, as applicable) have been used to measure air flow through the storage bin. Since there are inevitable air leaks in an air system of this type, the computations for energy to and from storage will be slightly in error, even though an attempt was made to account for air leakage wherever possible.

During the 12 month period an approximate total of 12.73 million Btu was delivered to storage and 4.44 million Btu was extracted for support of the space heating load. However, the storage subsystem was inactive during the summer months (June, July and August), so these values essentially represent performance for a nine month, rather than a 12 month period. During these same nine months the net change in stored energy was -0.11 million Btu, which leads to an overall storage efficiency of 0.34 and a total heat loss from storage of 8.40 million Btu. The average temperature of storage during the active period was 108°F, and for the full 12 months it was 102°F.

It will be noted that almost two times as much energy was lost from storage as was removed for support of the space heating load during the active period. It is suspected that the seal around the cover of the unit is defective to some degree, thus allowing this large amount of leakage. During seasonal transitional months, such as April, May, September and October, this leakage can result in some discomfort for the occupants and also cause a higher than normal cooling load. However, during the winter months the losses represent an uncontrolled reduction in the overall space heating load. The ramifications of this uncontrolled heat input to the dwelling will be discussed in greater detail in subsequent sections.

TABLE 3.2.2-1

STORAGE SUBSYSTEM PERFORMANCE

Month	Energy To Storage (Million Btu)	Energy From Storage (Million Btu)	Change In Stored Energy (Million Btu)	Storage Efficiency	Storage Average Temperature (°F)
Nov 78	0.61	0.19	-0.26	-0.12	116
Dec 78	1.53	0.60	-0.03	0.38	96
Jan 79	0.47	0.31	-0.15	0.34	84
Feb 79	2.02	1.25	0.23	0.73	91
Mar 79	2.30	1.04	-0.09	0.42	122
Apr 79	2.28	0.74	0.12	0.38	122
May 79	1.04	0.09	-0.23	-0.14	114
Jun 79	0	0	0.03	1.00	83
Jul 79	0	0	0.04	1.00	84
Aug 79	0	0	-0.01	1.00	86
Sep 79	1.17	0.04	0.29	0.28	109
Oct 79	1.31	0.18	0.01	0.15	122
Total	12.73	4.44	-0.11*	--	--
Average	1.06	0.37	-0.01*	0.34*	108*

*These values based on only the nine months that the storage subsystem was active. The values for June, July and August are not included in the total or averages.

3.2.3 Hot Water Subsystem

The performance of the hot water subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total hot water load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy.

The performance of the Solaron Akron hot water subsystem is presented in Table 3.2.3-1. The value for auxiliary energy supplied in Table 3.2.3-1 is the gross energy supplied to the auxiliary system. The value of auxiliary energy supplied multiplied by the auxiliary system efficiency gives the auxiliary thermal energy actually delivered to the load. The difference between the sum of auxiliary thermal energy plus solar energy and the hot water load is equal to the thermal (standby) losses from the hot water subsystem.

The measured solar fraction in Table 3.2.3-1 is an average weighted value for the month based on the ratio of solar energy in the hot water tank to the total energy in the hot water tank when a demand for hot water exists. This value is dependent on the daily profile of hot water usage. It does not represent the ratio of solar energy supplied to the sum of solar plus auxiliary thermal energy supplied shown in the Table.

For the 12 month period from November 1978 through October 1979, the solar energy system supplied a total of 7.29 million Btu to the hot water subsystem. However, the hot water subsystem itself effectively delivered 5.98 million Btu to the hot water load. The difference represents losses attributable to the preheat tank and its associated plumbing. The total hot water load for this period was 20.50 million Btu, and the weighted average monthly solar fraction was 26 percent.

TABLE 3.2.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Hot Water Parameters				Energy Consumed (Million Btu)			Weighted Solar Fraction (Percent)
	Load (Million Btu)	Gallons Used	Temperatures (°F)		Solar	Auxiliary Thermal	Auxiliary	
			Supply	Delivery				
Nov 78	1.53	3,043	66*	126	0.47	1.54	1.54	18
Dec 78	2.18	3,561	60*	127	0.40	2.04	2.04	17
Jan 79	2.44	3,665	55	127	0.18	2.37	2.37	10
Feb 79	2.02	2,942	56	127	0.54	1.76	1.76	21
Mar 79	1.80	2,633	54	127	0.82	1.97	1.97	34
Apr 79	1.71**	3,092**	59**	127**	0.76	1.94	1.94	26**
May 79***	2.00	3,722	65	126	0.30	1.91	1.91	14
Jun 79	1.37	2,736	69	127	0.71	0.97	0.97	39
Jul 79	1.48	3,154	73	127	0.79	1.00	1.00	39
Aug 79	1.39	3,166	75	127	0.79	0.96	0.96	40
Sep 79	1.27	2,835	75	126	0.96	0.71	0.71	54
Oct 79	1.31	2,552	70	126	0.57	1.06	1.06	31
Total	20.50	37,101	--	--	7.29	18.23	18.23	--
Average	1.71	3,092	65	127	0.61	1.52	1.52	26

* T302 was defective until December 13, 1978. Therefore these values are approximate.

** W302 was defective during most of April. The values presented in the table have been estimated from the applicable data for the other 11 months.

***The collector array did not operate from May 11 to May 30 due to a control problem.

The monthly average hot water load during the reporting period was 1.71 million Btu. This is based on an average daily consumption of 102 gallons, delivered at an average temperature of 127°F and supplied to the system at an average temperature of 65°F. The temperature of the supply water ranged from a low of 54°F in March to a high of 75°F in August and September.

Each month an average of 0.50 million Btu of solar energy from the preheat tank and 1.52 million Btu of auxiliary thermal (electrical) energy were supplied to support the hot water load. Since the average monthly hot water load was 1.71 million Btu, an average of 0.31 million Btu was lost from the hot water tank each month. In addition, an average of 0.02 million Btu of operating energy was required to support the hot water subsystem each month.

There were some instrumentation problems relating to the hot water subsystem during the reporting period. Both the supply water temperature sensor (T302) and flow sensor (W302) failed at different times for periods of approximately one to one and one half months. The affected parameters have been noted in Table 3.2.3-1 and it is believed that the values presented there constitute a reasonable approximation to the true values for these parameters.

In addition to the instrumentation problems there was a control problem that developed during the summer months. This problem resulted in cyclic operation of both the hot water recirculation pump (P1) and the ECSS blower (B1). The problem was corrected with the installation of a differential controller in the early fall, but performance of the hot water subsystem was probably degraded somewhat from July through September.

3.2.4 Space Heating Subsystem

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the heating solar fraction. The calculated heating solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total space heating load supported by solar energy.

The performance of the Solaron Akron space heating subsystem is presented in Table 3.2.4-1. For the 12 month period from November 1978 through October 1979, the solar energy system supplied a measured total of 3.23 million Btu to the space heating load. The total measured heating load for this period was 15.09 million Btu, and the average monthly solar fraction was 21 percent.

It must be emphasized that all values presented in this section relating to the performance of the space heating subsystem are based on measured parameters. In other words the space heating load, solar contribution and solar fraction are all determined based on the measured output of the space heating subsystem. These measured values do not include any of the various solar energy losses that are present in the system. However, solar energy losses are generally added to the interior of the house and, as such, represent an uncontrolled (unmeasured) contribution to the space heating load. At the Solaron Akron site these solar energy losses occur during energy transport between the various subsystems (primarily due to duct leakage), from the storage bin and, to a lesser extent, the hot water preheat tank. During the primary heating season (October through April) a total of approximately 23.12 million Btu of solar energy was added to the interior of the

TABLE 3.2.4-1

HEATING SUBSYSTEM PERFORMANCE

Month	Heating Parameters			Energy Consumed (Million Btu)			Measured Solar Fraction (Percent)
	Load (Million Btu)	Temperatures (°F)		Solar	Auxiliary Thermal	Auxiliary	
		Building	Outdoor				
Nov 78	1.19	70	43	0.20	1.15	0.47	16
Dec 78	2.43	68	32	0.50	2.99	1.78	21
Jan 79	4.77	68	21	0.42	5.03	2.43	9
Feb 79	4.34	69	19	0.66	4.26	2.57	15
Mar 79	1.22	71	42	0.76	1.20	0.53	63
Apr 79	0.77	71	47	0.48	0.25	0.08	62
May 79	0.05	73	58	0.05	0.02	0.01	88
Jun 79	0	76	68	0	0	0	--
Jul 79	0	79	71	0	0	0	--
Aug 79	0	77	69	0	0	0	--
Sep 79	0.04	75	64	0.04	0	0	100
Oct 79	0.28	71	51	0.12	1.15	0.44	41
Total	15.09	--	--	3.23	16.05	8.31	--
Average	1.26	72	49	0.27	1.34	0.69	21*

*Average solar fraction is the ratio of Total Solar Energy to Total Load.

house through these various losses. This amount of uncontrolled solar energy added was over seven times greater than the measured amount of solar energy supplied to the space heating subsystem during the primary heating season. As such, this uncontrolled input of solar energy to the house represents a significant contribution to the space heating load.

In addition to the solar energy system losses there are also losses of auxiliary energy from the off-peak system. During the primary heating season these losses totaled approximately 5.96 million Btu and also contributed to the space heating load, although to a lesser extent than the solar energy system losses.

It is interesting to note the dramatic change that occurs in the calculated space heating subsystem performance when all the losses are included in the computations for the primary heating season. By adding the total amount of losses (solar plus auxiliary) to the measured load, and adding the solar losses only to the solar contribution, the heating solar fraction increases to 60 percent. This is almost three times greater than the computed value of 21 percent.

One final point relating to the uncontrolled solar energy losses should be considered. Even though these losses provide a benefit during the heating season, they represent a burden to the cooling load during the transitional periods of the year. If any air conditioning is done, the cost of operating the cooling unit will be increased. If no air conditioning is used, the occupants of the house may have to suffer some unnecessary discomfort due to higher interior temperature levels.

During the 12 month reporting period a total of 8.31 million Btu of auxiliary energy was consumed by the space heating subsystem when it was operating in the various auxiliary heating modes. Of this total, 6.95 million Btu were

consumed by the heat pump compressor and 1.36 million Btu were consumed by the heat strips. Since 14.69 million Btu were added to the auxiliary heating system by the heat pump, the average COP of the heat pump was approximately 2.11. This is in contrast to the average COP of approximately 1.11 for the entire off-peak system. The average overall system COP of 1.11 is based on a comparison of the total amount of power consumed by the heat pump compressor and pump P2 versus the total energy delivered to the auxiliary system at HX2 (reference Figure 2-1). As such, it is a more accurate indicator of the auxiliary heat pump system performance because it represents the actual ratio of energy sought to energy that costs. Power unnecessarily consumed by either pump P2 or the heat pump compressor due to control system or other problems is included, so the average system COP represents all phases of system operation.

4. OPERATING ENERGY

Operating energy for the Solaron Akron Solar Energy System is defined as the energy required to transport solar energy to the point of use. Total operating energy for this system consists of energy collection and storage subsystem operating energy, hot water subsystem operating energy and space heating subsystem operating energy. Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. Measured monthly values for subsystem operating energy are presented in Table 4-1.

Total system operating energy for the Solaron Akron Solar Energy System is that electrical energy required to operate the blowers in the ECSS loop (B1) and the air distribution duct (B2), the pumps in the DHW subsystem (P1) and the auxiliary heat pump system (P2), and the heat pump outside fan. These are shown as EP100, EP400, EP301, EP404 and EP403, respectively, in Figure 2-1. Although additional electrical energy is required to operate the three motor driven dampers and the control system for the installation, it is not included in this report. These devices are not monitored for power consumption and the power they consume is inconsequential when compared to the fan and pump motors.

During the 12 month reporting period, a total of 5.22 million Btu (1529 kwh) of operating energy was consumed. However, this includes the energy required to operate the blower in the air distribution duct and the pump and outside fan in the heat pump system, and that energy would be required whether or not the solar energy system was being utilized for space heating. Therefore, the energy consumed by these devices is not considered to be solar peculiar operating energy, even though it is included as part of the space heating subsystem operating energy.

TABLE 4-1

OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Hot Water Operating Energy (Million Btu)	Space Heating Operating Energy (Million Btu)	Total System Operating Energy (Million Btu)
Nov 78	0.135	0.017	0.188	0.340
Dec 78	0.116	0.019	0.730	0.865
Jan 79	0.070	0.009	1.033	1.112
Feb 79	0.148	0.025	0.739	0.912
Mar 79	0.219	0.030	0.183	0.432
Apr 79	0.194	0.028	0.066	0.288
May 79	0.099	0.010	0.004	0.113
Jun 79	0.179	0.021	0	0.200
Jul 79	0.190	0.025	0	0.215
Aug 79	0.160	0.030	0	0.190
Sep 79	0.213	0.039	0.001	0.253
Oct 79	0.144	0.025	0.128	0.297
Total	1.867	0.278	3.072	5.217
Average	0.156	0.023	0.256	0.435

A total of 2.15 million Btu (630 kwh) of operating energy was required to support the pump and fan that are unique to the solar energy system during the reporting period. Of this total, 1.87 million Btu were allocated to the Energy Collection and Storage Subsystem (ECSS) and 0.28 million Btu were allocated to the DHW Subsystem. Since a measured 9.21 million Btu of solar energy was delivered to system loads during the reporting period, a total of 0.23 million Btu (67 kwh) of operating energy was required for each one million Btu of solar energy delivered to the system loads.

5. ENERGY SAVINGS

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution, and the resulting energy savings are adjusted to reflect the coefficient of performance (COP) of the auxiliary source being supplanted by solar energy.

The Solaron Akron Solar Energy System has a heat pump for auxiliary space heating purposes. However, the heat pump is not used as a stand-alone unit, but rather in conjunction with an off-peak storage tank and associated hardware. As discussed in the Space Heating Subsystem section, the average COP for the overall heat pump system (not including the electrical strip heaters) was approximately 1.11 for the reporting period. Auxiliary energy for the heat strips and hot water heating is also provided by electricity and the COP for both the strips and hot water heating element is considered to be 1.0 for computational purposes.

Energy savings for the 12 month reporting period are presented in Table 5-1. During this time the system realized a gross electrical energy savings of 9.03 million Btu, which is the amount of solar energy supplied to the hot water subsystem and space heating subsystem (with appropriate COP adjustment). Since 0.28 million Btu were required to operate the hot water subsystem recirculation pump, the net savings for the hot water subsystem amounted to 5.70 million Btu. The net savings for the space heating subsystem, which is not charged with any operating energy deduction, totaled 3.05 million Btu. The ECSS blower consumed 1.87 million Btu of operating energy, so the net electrical energy savings for the entire solar energy system were 6.88 million Btu (2,015 kwh).

TABLE 5-1

ENERGY SAVINGS

Month	Electrical Energy Savings (Million Btu)		ECSS Operating Energy (Million Btu)	Net Electrical Energy Savings		Fossil Equivalent At Source (Million Btu)
	Hot Water	Space Heating		(Million Btu)	(kwh)	
Nov 78	0.211*	0.179	0.135	0.255*	75*	0.850*
Dec 78	0.342*	0.470	0.116	0.696*	204*	2.320*
Jan 79	0.220	0.412	0.070	0.562	165	1.873
Feb 79	0.416	0.636	0.148	0.904	265	3.013
Mar 79	0.631	0.720	0.219	1.132	332	3.773
Apr 79	0.604*	0.442	0.194	0.852*	250*	2.840*
May 79	0.273	0.044	0.099	0.218	64	0.727
Jun 79	0.585	0	0.179	0.406	119	1.353
Jul 79	0.634	0	0.190	0.444	130	1.480
Aug 79	0.609	0	0.160	0.449	132	1.497
Sep 79	0.743	0.036	0.213	0.566	166	1.887
Oct 79	0.431	0.106	0.144	0.393	115	1.310
Total	5.699	3.045	1.867	6.877	2,015	22.923
Average	0.475	0.254	0.156	0.573	168	1.910

*The DHW subsystem contribution to electrical energy savings during these months is based on estimated performance of the subsystem.

It should be noted that all values relating to space heating savings are based only on the measured solar energy contribution to the space heating load. As discussed in the Space Heating Subsystem section, approximately 23.12 million Btu of solar energy were added to the interior of the house through various losses during the primary heating season. This uncontrolled addition of solar energy to the house, had it been included in the space heating subsystem computations, would have altered the space heating (and total system) savings tremendously. This additional but unreported savings can be approximately quantified by determining the ratio of auxiliary energy supplied by the heat pump (88 percent) and the heat strips (12 percent), splitting the losses by this ratio, and dividing by the appropriate COP (1.11 for the heat pump and 1.0 for the heat strips). This procedure yields a savings of 21.10 million Btu (6182 kwh), again over seven times greater than thc reported space heating savings of 3.05 million Btu. If the losses were taken into account, the net savings for the complete solar energy system would have been 27.98 million Btu (8198 kwh), as opposed to the reported value of 6.88 million Btu.

6.0 MAINTENANCE

This section provides a summary of all known maintenance visits made to the Solaron Akron site from the time it went on line until the closing of the data assessment period.

August 22, 1978

- Release air entrained in system and reprime system

October 7, 1978

- Set off-peak tank charging system from cooling mode to off

December 12-13, 1978

- Replace off-peak timer with a unit incorporating a spring reserve
- Check filters in off-peak system
- Set off-peak charging system from off to heating mode

February 8, 1979

- Replace damper motor for MD3

March 27-30, 1979

- Seal air leaks in ductwork

October 9-11, 1979 (approximate)

- Replace controller in collector loop
- Adjust off-peak control system

NOTE: No formal report was received for this maintenance visit. Therefore, the above data may be incomplete.

7. SUMMARY AND CONCLUSIONS

The following paragraphs provide a brief summary of all pertinent parameters for the Solaron Akron Solar Energy System for the period from November 1978 to October 1979. A more detailed discussion can be found in the applicable preceding sections.

During the reporting period, the measured daily average incident insolation in the plane of the collector array was 1,118 Btu/Ft^2. This was five percent below the long-term daily average of 1,179 Btu/Ft^2. During the same period the measured average outdoor ambient temperature was 49°F. This was one degree below the long-term average of 50°F. As a result 6,528 heating degree-days were accumulated, as compared to the long-term average of 6,224 heating degree-days.

The solar energy system satisfied 24 percent of the total measured load (hot water plus space heating) during the 12 month reporting period. This agreed closely with the expected value of 22 percent for the entire reporting period. However, there were considerable variations between the measured and expected solar fraction at the monthly level. The exact cause for the monthly variations is not known, but there were several possibilities. These were discussed at length in the System Performance section of this report.

A total of 222.63 million Btu of incident solar energy was measured in the plane of the collector array during the reporting period. The system collected 40.78 million Btu of the available energy, which represents a collector array efficiency of 18 percent. During periods when the collector array was active, a total of 104.42 million Btu was measured in the plane of the collector array. Therefore, the operational collector efficiency was 39 percent. However, as noted in prior sections, the air flow correction factors for November through March were suspect. This means that the values for solar energy collected and the two collector array efficiencies were somewhat high during these five months.

During the reporting period a total of 12.73 million Btu of solar energy was delivered to the storage bin. During this same time 4.44 million Btu were removed from storage for support of the space heating load. However, the storage subsystem was not used during the summer months as there were no space heating requirements during this time. During the active period the net change in stored energy was -0.11 million Btu and 8.40 million Btu were lost from storage. The average storage efficiency was 0.34 and the average temperature was 108°F.

The hot water load for the 12 month reporting period was 20.50 million Btu. A total of 5.98 million Btu of solar energy and 18.23 million Btu of auxiliary energy were applied to the hot water load, which represents a weighted hot water solar fraction of 26 percent. The average daily consumption of hot water was 102 gallons, delivered at an average temperature of 127°F. A total of 3.71 million Btu was lost from the hot water tank during the reporting period. The subsystem extracted 7.29 million Btu of solar energy from the collector loop, so there were additional transport and preheat tank losses of 1.31 million Btu.

The measured space heating load was 15.09 million Btu for the full reporting period. However, all of this space heating demand occurred during the September through May time period. During the seven month primary heating season (October through April) the measured space heating load was 15.00 million Btu, or 99 percent of the total. The heating solar fraction for both the full 12 month period and the primary heating season was 21 percent. During the seven month heating season a total of 3.14 million Btu of measured solar energy and 11.86 million Btu of auxiliary thermal energy were actually delivered to the space heating load, and this energy maintained an average building temperature of 70°F. However, a total of 16.03 million Btu of auxiliary thermal energy was actually added to the space heating subsystem by the compressor and heat strips during the primary heating season when the system was operating in a defined heating mode.

A total of 2.15 million Btu, or 630 kwh, of electrical operating energy was required to support the solar energy system during the 12 month reporting period. This does not include the electrical energy required to operate the fan, pump or heat pump in the auxiliary system. These would be required for operation of the space heating subsystem regardless of the presence of the solar energy system.

Gross electrical energy savings for the 12 month reporting period were 9.03 million Btu. However, when the 2.15 million Btu of electrical operating energy is taken into account, the net electrical energy savings were 6.88 million Btu, or 2,015 kwh. If a 30 percent efficiency is assumed for power generation and distribution, then the net electrical energy savings translate into a savings of 22.92 million Btu in generating station fuel requirements. It should also be noted that the electrical energy savings are based only on the measured amount of solar energy delivered to the space heating subsystem. As discussed in Section 5., the energy savings will increase considerably if the uncontrolled solar energy input to the building is considered.

In general, the performance of the Solaron Akron Solar Energy System was somewhat difficult to assess for the November 1978 through October 1979 time period. The problems relating to the control systems, various solar energy leakages, air flow correction factors and instrumentation cause a significant amount of subjectivity to be involved in the performance assessment for this solar energy system. Had these problems not been present, it is felt that this system would have exhibited a reasonably high level of measured performance.

8. REFERENCES

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APPENDIX A

DEFINITION OF PERFORMANCE FACTORS

AND

SOLAR TERMS

APPENDIX A

DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the primary storage medium, the transport loops between these, and other components in the system design which are necessary to mechanize the collector and storage equipment.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

- ECSS OPERATING ENERGY (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount incident solar energy on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the incident energy on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

STORAGE PERFORMANCE

The storage performance is characterized by the relationships among the energy delivered to storage, removed from storage, and the subsequent change in the amount of stored energy.

- ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.
- ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.
- CHANGE IN STORED ENERGY (STECH) is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).
- STORAGE AVERAGE TEMPERATURE (TST) is the mass-weighted average temperature of the primary storage medium.
- STORAGE EFFICIENCY (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow to and from the subsystem, as well as an accounting of internal energy. The energy into the subsystem is composed of auxiliary electrical or fossil fuel, solar energy, and the operating energy for the subsystem. In addition, the solar fraction for the subsystem is tabulated. The load of the subsystem is tabulated and used to compute the estimated electrical and fossil fuel savings of the subsystem. The load of the subsystem is further identified by tabulating the supply water temperature, and the outlet hot water temperature, and the total hot water consumption.

- HOT WATER LOAD (HWL) is the amount of energy required to heat the amount of hot water demanded at the site from the incoming temperature to the desired outlet temperature.

- SOLAR FRACTION OF LOAD (HWSFR) is the percentage of the load demand which is supported by solar energy.

- SOLAR ENERGY USED (HWSE) is the amount of solar energy supplied to the hot water subsystem.

- OPERATING ENERGY (HWOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HWAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- AUXILIARY ELECTRICAL FUEL (HWAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (HWSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- SUPPLY WATER TEMPERATURE (TSW) is the average inlet temperature of the water supplied to the subsystem.

- AVERAGE HOT WATER TEMPERATURE (THW) is the average temperature of the outlet water as it is supplied from the subsystem to the load.

- HOT WATER USED (HWCSM) is the volume of water used.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.
- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.
- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.
- OPERATING ENERGY (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.
- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.
- AUXILIARY ELECTRIC FUEL (HAE) is the amount of electrical energy supplied directly to the subsystem.
- ELECTRICAL ENERGY SAVINGS (HSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- ELECTRICAL ENERGY SAVINGS (HSVE) is the cost of the operating energy (HOPE) required to support the solar energy portion of the space heating subsystem.

- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.

- AMBIENT TEMPERATURE (TA) is the average ambient dry bulb temperature at the site.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the program. It is tabulated in this data report for two purposes--as a measure of the conditions prevalent during the operation of the system at the site, and as an historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION (SE) is accumulated total incident solar energy upon the gross collector array measured at the site.
- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.
- WIND DIRECTION (WDIR) is the average direction of the prevailing wind.
- WIND SPEED (WIND) is the average wind speed measured at the site.
- DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR

SOLARON AKRON

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR SOLARON AKRON

I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60)\ \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in Btu/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [\text{M100} \times \Delta H] \times \Delta\tau$$

where M100 is the mass flow rate of the heat transfer fluid, in lb_m/min, and ΔH is the enthalpy change, in Btu/lb_m, of the fluid as it passes through the heat exchanging component.

For a liquid system ΔH is generally given by

$$\Delta H = \overline{C}_p\ \Delta T$$

where $\overline{C}_p$ is the average specific heat, in Btu/(lb_m-°F), of the heat transfer fluid and ΔT, in °F, is the temperature differential across the heat exchanging component.

For an air system ΔH is generally given by

$$\Delta H = H_a(T_{out}) - H_a(T_{in})$$

where $H_a(T)$ is the enthalpy, in Btu/lb_m, of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

$H_a(T)$ can have various forms, depending on whether or not the humidity ratio of the transport air remains constant as it passes through the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60)\ \Sigma\ [\text{EP100}] \times \Delta\tau$$

where EP100 is the measured power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document, given in the list of references, was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

II. PERFORMANCE EQUATIONS

The performance equations for Solaron Akron used for the data evaluation of this report are contained in the following pages and have been included for technical reference and information.

EQUATIONS USED IN MONTHLY PERFORMANCE ASSESSMENT

NOTE: MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 2-1

AVERAGE AMBIENT TEMPERATURE (°F)

$$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$$

AVERAGE BUILDING TEMPERATURE (°F)

$$TB = (1/60) \times \Sigma\ T601 \times \Delta\tau$$

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

$$TDA = (1/360) \times \Sigma\ T001 \times \Delta\tau$$

FOR $\pm$ 3 HOURS FROM SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT^2)

$$SE = (1/60) \times \Sigma\ I001 \times \Delta\tau$$

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

$$SEOP = (1/60) \times \Sigma\ [I001 \times CLAREA] \times \Delta\tau$$

WHEN THE COLLECTOR LOOP IS ACTIVE

HUMIDITY RATIO FUNCTION (BTU/LBM-°F)

$$HRF = 0.24 + 0.444 \times HR$$

WHERE 0.24 IS THE SPECIFIC HEAT AND HR IS THE HUMIDITY RATIO OF THE TRANSPORT AIR. THIS FUNCTION IS USED WHENEVER THE HUMIDITY RATIO WILL REMAIN CONSTANT AS THE TRANSPORT AIR FLOWS THROUGH A HEAT EXCHANGING DEVICE

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$$SECA = \Sigma\ [(M101 \times (T150-T100) + (M100-M101) \times (T150-T001)) \times HRF] \times \Delta\tau$$

NOTE THAT THIS EQUATION ACCOUNTS FOR LEAKAGE FLOW FROM THE OUTSIDE ENVIRONMENT INTO THE COLLECTOR ARRAY. ALSO, IN THE EVENT THAT THE COLLECTOR INLET TEMPERATURE EXCEEDS 159°F, T100 IS REPLACED BY (T102-3)°F.

SPACE HEATING LOAD (BTU)

$$HL = \Sigma\,[M600 \times HRF \times (T450 - T601)] \times \Delta\tau$$

WHENEVER THE SYSTEM IS IN A SPACE HEATING MODE

AVERAGE TEMPERATURE OF STORAGE (°F)

$$TST1 = (1/60) \times \Sigma\,[(T200 + T201 + T202)/3] \times \Delta\tau$$

SOLAR ENERGY TO STORAGE (BTU)

$$STEI = \Sigma\,[0.5 \times (M100 + M101) \times HRF \times (T102 - T152)] \times \Delta\tau$$

SOLAR ENERGY FROM STORAGE (BTU)

$$STEO = \Sigma\,[(M600 - M100T) \times HRF \times (T102 - T152)] \times \Delta\tau$$

WHERE M100T IS A TERM THAT ACCOUNTS FOR ANY FLOW THAT DOES NOT GO THROUGH STORAGE DUE TO DAMPER LEAKAGE

SOLAR ENERGY TO LOAD FROM STORAGE (BTU)

$HSE3 = HL$ WHEN HEATING FROM STORAGE

SOLAR ENERGY TO LOAD FROM COLLECTOR ARRAY (BTU)

$HSE2 = HL$ WHEN HEATING FROM THE COLLECTOR ARRAY

ECSS OPERATING ENERGY (BTU)

$$CSOPE = 56.8833 \times \Sigma\, EP100 \times \Delta\tau$$

HOT WATER CONSUMED (GALLONS)

$$HWCSM = \Sigma WD302 \times \Delta\tau$$

ENTHALPY FUNCTION FOR WATER (BTU/LBM)

$$HWD\,(T_2, T_1) = \int_{T_1}^{T_2} C_p(T)\,dT$$

THIS FUNCTION COMPUTES THE ENTHALPY CHANGE OF WATER AS IT PASSES THROUGH A HEAT EXCHANGING DEVICE.

HOT WATER LOAD (BTU)

$$HWL = \Sigma\ [M302 \times HWD(T352,\ T302)] \times \Delta\tau$$

SOLAR ENERGY TO HOT WATER SUBSYSTEM (BTU)

$$HWSE = \Sigma\ [M301 \times HWD\ (T351,\ T301)] \times \Delta\tau$$

SOLAR ENERGY TO HOT WATER LOAD (BTU)

$$HWSE1 = \Sigma\ [M302 \times HWD\ (T303,\ T302)] \times \Delta\tau \qquad \text{IF } M301 = 0$$

$$HWSE1 = \Sigma\ [M302 \times HWD\ (T351,\ T302)] \times \Delta\tau \qquad \text{IF } M301 \geq M302$$

$$HWSE1 = \Sigma\ [M302 \times HWD\ (TX,\ T302)] \times \Delta\tau \qquad \text{IF } M301 < M302$$

WHERE

$$TX = (T351 \times M301 + T303 \times (M302-M301))/M302$$

HOT WATER SUBSYSTEM OPERATING ENERGY (BTU)

$$HWOPE = 56.8833 \times \Sigma\ EP301 \times \Delta\tau$$

HOT WATER SUBSYSTEM AUXILIARY ELECTRICAL FUEL ENERGY (BTU)

$$HWAE = 56.8833 \times \Sigma\ EP302 \times \Delta\tau$$

SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

$$HOPE = 56.8833 \times \Sigma\ [EP400 + EP403 + EP404] \times \Delta\tau$$

WHENEVER SYSTEM OPERATING IN A HEATING MODE

AUXILIARY ELECTRICAL FUEL ENERGY TO HEAT STRIPS (BTU)

$$HAE1 = 56.8833 \times \Sigma\ EP401 \times \Delta\tau$$

AUXILIARY ELECTRICAL FUEL ENERGY TO HEAT PUMP COMPRESSOR (BTU)

$$HAE3 = 56.8833 \times \Sigma\ [EP402 - EP403] \times \Delta\tau$$

WHEN HEATING DIRECTLY FROM THE HEAT PUMP

$$HAE4 = 56.8833 \times \Sigma\ [EP402 - EP403] \times \Delta\tau$$

WHEN CHARGING OFF PEAK STORAGE WITH HEAT PUMP

HEAT PUMP SYSTEM POWER (BTU)

$$HPPWR = 56.8833 \times \Sigma\ [EP402 + EP404] \times \Delta\tau$$

WHEN HEAT PUMP IS IN A HEATING MODE

ENERGY DELIVERED BY HEAT PUMP SYSTEM (BTU)

$$HTHPDIR = \Sigma\ [M400 \times HWD\ (T401,\ T451)] \times \Delta\tau$$

WHEN HEATING DIRECTLY FROM THE HEAT PUMP

$$HTHPSTO = \Sigma\ [M400 \times HWD\ (T401,\ T451)] \times \Delta\tau$$

WHEN HEATING FROM OFF PEAK STORAGE TANK

AUXILIARY THERMAL ENERGY FROM HEAT PUMP (BTU)

$$HAT3 = \Sigma\ [M202 \times HWD\ (T257,\ T207)] \times \Delta\tau$$

WHEN HEATING DIRECTLY FROM THE HEAT PUMP

$$HAT4 = \Sigma\ [M202 \times HWD\ (T257,\ T207)] \times \Delta\tau$$

WHEN CHARGING OFF PEAK STORAGE WITH HEAT PUMP

SUPPLY WATER TEMPERATURE (°F)

$$TSW = T302$$

HOT WATER TEMPERATURE (°F)

$$THW = T352$$

BOTH TSW AND THW ARE COMPUTED ONLY WHEN FLOW EXISTS IN THE SUBSYSTEM, OTHERWISE THEY ARE SET EQUAL TO THE VALUES OBTAINED DURING THE PREVIOUS FLOW PERIOD.

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

SEA = CLAREA x SE

COLLECTED SOLAR ENERGY (BTU/FT^2)

SEC = SECA/CLAREA

COLLECTOR ARRAY EFFICIENCY

CAREF = SECA/SEA

CHANGE IN STORED ENERGY (BTU)

STECH = STECH1 - $STECH\ 1_p$

WHERE THE SUBSCRIPT $_p$ REFERS TO A PRIOR REFERENCE VALUE

STORAGE EFFICIENCY

STEFF = (STECH + STEO)/STEI

ENERGY DELIVERED FROM ECSS TO LOAD SUBSYSTEMS (BTU)

CSEO = STEO + HSE2 + HWSE

AUXILIARY THERMAL ENERGY TO HOT WATER SUBSYSTEM (BTU)

HWAT = HWAE

HOT WATER SOLAR FRACTION (PERCENT)

HWSFR = 100 x HWTKSE/(HWTKSE + HWTKAUX)

WHERE HWTKSE AND HWTKAUX REPRESENT THE CURRENT SOLAR AND AUXILIARY ENERGY CONTENT OF THE HOT WATER TANK

HOT WATER ELECTRICAL ENERGY SAVINGS (BTU)

HWSVE = HWSE1 - HWOPE

SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$HSE = HSE2 + HSE3$

AUXILIARY ELECTRICAL ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$HAE = HAE1 + HAE3 + HAE4$

TOTAL ENERGY DELIVERED BY HEAT PUMP SYSTEM (BTU)

$HLHP = HTHPSTO + HTHPDIR$

AUXILIARY THERMAL ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$HAT = HAE1 + HAT3 + HAT4$

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

$HSFR = 100 \times HSE/HL$

SPECIAL HEAT PUMP TERMS

NORMALIZED CAPACITY

$CAPN = 0.325 + TA \times (0.0162-0.00005 \times TA)$

HEAT PUMP FRACTION

$HPF = 1$ $\qquad TA > 40$

$HPF = 1.11 \times CAPN \times (TB-40)/(TB-TA)$ $\qquad 2 \leq TA \leq 40$

$HPF = 0$ $\qquad TA < 2$

HEAT PUMP OVERALL SYSTEM COP

$HCOP = HLHP/HPPWR$

WHERE HCOP IS BASED ON A TOTAL OF EIGHT

MONTHS OF SYSTEM OPERATION

SPACE HEATING SUBSYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

HSVE = HSE x (HPF/HCOP + 1 - HCOP) IF TA $\geq$ 2

HSVE = 0.5 x HSE x (1 + HCOP)/HCOP IF TA < 2

SYSTEM LOAD (BTU)

SYSL = HL + HWL

SOLAR FRACTION OF SYSTEM LOAD (PERCENT)

SFR = (HL x HSFR + HWL x HWSFR)/SYSL

SYSTEM OPERATING ENERGY (BTU)

SYSOPE = HWOPE + HOPE + CSOPE

AUXILIARY THERMAL ENERGY TO LOADS (BTU)

AXT = HWAT + HAT

AUXILIARY ELECTRICAL ENERGY TO LOADS (BTU)

AXE = HWAE + HAE

SOLAR ENERGY TO LOAD SUBSYSTEMS (BTU)

SEL = HWSE + HSE

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SEL/SEA

TOTAL ELECTRICAL ENERGY SAVINGS (BTU)

TSVE = HWSVE + HSVE - CSOPE

TOTAL ENERGY CONSUMED (BTU)

TECSM = SYSOPE + AXE + SECA

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/(AXE + SYSOPE) x 3.33

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

EQUATIONS USED IN MONTHLY PERFORMANCE ASSESSMENT

NOTE: MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 2-1

AVERAGE AMBIENT TEMPERATURE (°F)

$$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$$

AVERAGE BUILDING TEMPERATURE (°F)

$$TB = (1/60) \times \Sigma\ T601 \times \Delta\tau$$

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

$$TDA = (1/360) \times \Sigma\ T001 \times \Delta\tau$$

FOR $\pm$ 3 HOURS FROM SOLAR NOON

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT^2)

$$SE = (1/60) \times \Sigma\ I001 \times \Delta\tau$$

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

$$SEOP = (1/60) \times \Sigma\ [I001 \times CLAREA] \times \Delta\tau$$

WHEN THE COLLECTOR LOOP IS ACTIVE

HUMIDITY RATIO FUNCTION (BTU/LBM-°F)

$$HRF = 0.24 + 0.444 \times HR$$

WHERE 0.24 IS THE SPECIFIC HEAT AND HR IS THE HUMIDITY RATIO OF THE TRANSPORT AIR. THIS FUNCTION IS USED WHENEVER THE HUMIDITY RATIO WILL REMAIN CONSTANT AS THE TRANSPORT AIR FLOWS THROUGH A HEAT EXCHANGING DEVICE

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$$SECA = \Sigma\ [(M101 \times (T150-T100) + (M100-M101) \times (T150-T001)) \times HRF] \times \Delta\tau$$

NOTE THAT THIS EQUATION ACCOUNTS FOR LEAKAGE FLOW FROM THE OUTSIDE ENVIRONMENT INTO THE COLLECTOR ARRAY. ALSO, IN THE EVENT THAT THE COLLECTOR INLET TEMPERATURE EXCEEDS 159°F, T100 IS REPLACED BY (T102-3)°F.

HOT WATER LOAD (BTU)

$$HWL = \Sigma\ [M302 \times HWD(T352,\ T302)] \times \Delta\tau$$

SOLAR ENERGY TO HOT WATER SUBSYSTEM (BTU)

$$HWSE = \Sigma\ [M301 \times HWD\ (T351,\ T301)] \times \Delta\tau$$

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SPACE HEATING SUBSYSTEM OPERATING ENERGY (BTU)

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WHENEVER SYSTEM OPERATING IN A HEATING MODE

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WHEN HEATING DIRECTLY FROM THE HEAT PUMP

$$HAE4 = 56.8833 \times \Sigma\ [EP402-EP403] \times \Delta\tau$$

WHEN CHARGING OFF PEAK STORAGE WITH HEAT PUMP

HEAT PUMP SYSTEM POWER (BTU)

$$HPPWR = 56.8833 \times \Sigma\ [EP402 + EP404] \times \Delta\tau$$

WHEN HEAT PUMP IS IN A HEATING MODE

ENERGY DELIVERED BY HEAT PUMP SYSTEM (BTU)

$$HTHPDIR = \Sigma\ [M400 \times HWD\ (T401,\ T451)] \times \Delta\tau$$

WHEN HEATING DIRECTLY FROM THE HEAT PUMP

$$HTHPSTO = \Sigma\ [M400 \times HWD\ (T401,\ T451)] \times \Delta\tau$$

WHEN HEATING FROM OFF PEAK STORAGE TANK

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SOLAR ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$HSE = HSE2 + HSE3$

AUXILIARY ELECTRICAL ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$HAE = HAE1 + HAE3 + HAE4$

TOTAL ENERGY DELIVERED BY HEAT PUMP SYSTEM (BTU)

$HLHP = HTHPSTO + HTHPDIR$

AUXILIARY THERMAL ENERGY TO SPACE HEATING SUBSYSTEM (BTU)

$HAT = HAE1 + HAT3 + HAT4$

SPACE HEATING SUBSYSTEM SOLAR FRACTION (PERCENT)

$HSFR = 100 \times HSE/HL$

SPECIAL HEAT PUMP TERMS

NORMALIZED CAPACITY

$CAPN = 0.325 + TA \times (0.0162-0.00005 \times TA)$

HEAT PUMP FRACTION

$HPF = 1$ $\quad TA > 40$

$HPF = 1.11 \times CAPN \times (TB-40)/(TB-TA)$ $\quad 2 \leq TA \leq 40$

$HPF = 0$ $\quad TA < 2$

HEAT PUMP OVERALL SYSTEM COP

$HCOP = HLHP/HPPWR$

WHERE HCOP IS BASED ON A TOTAL OF EIGHT MONTHS OF SYSTEM OPERATION

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

The environmental estimates given in this appendix provide a point of reference for evaluation of weather conditions as reported in the Monthly Performance Reports and Solar Energy System Performance Evaluations issued by the Solar Heating, Cooling and Hot Water Development Program. As such, the information presented can be useful in prediction of long-term system performance.

Environmental estimates for this site include the following monthly averages: extraterrestrial insolation, insolation on a horizontal plane at the site, insolation in the tilt plane of the collection surface, ambient temperature, heating degree-days, and cooling degree-days. Estimation procedures and data sources are detailed in the following paragraphs.

The preferred source of long-term temperature and insolation data is "Input Data for Solar Systems" (IDSS) [1] since this has been recognized as the solar standard. The IDSS data are used whenever possible in these environmental estimates for both insolation and temperature related sources; however, a secondary source used for insolation data is the Climatic Atlas of the United States [2], and for temperature related data, the secondary source is "Local Climatological Data" [3].

Since the available long-term insolation data are only given for a horizontal surface, solar collection subsystem orientation information is used in an algorithm [4] to calculate the insolation expected in the tilt plane of the collector. This calculation is made using a ground reflectance of 0.2.

REFERENCES

[1] Cinquemani, V., et al. "Input Data for Solar Systems." Prepared for the U.S. Department of Energy by the National Climatic Center, Asheville, NC, 1978.

[2] United States Department of Commerce, Climatic Atlas of the United States, Environmental Data Service, Reprinted by the National Oceanic and Atmospheric Administration, Washington, DC, 1977.

[3] United States Department of Commerce, "Local Climatological Data," Environmental Data Service, National Oceanic and Atmospheric Administration, Asheville, NC, 1977.

[4] Klein, S. A., "Calculation of Monthly Average Insolation on Tilted Surfaces," Joint Conference 1976 of the International Solar Energy Society and the Solar Energy Society of Canada, Inc., Winnipeg, August 15-20, 1976.

SITE: SOLARON AKRON 104. LOCATION: AKRON OH

ANALYST: D. GREGORY FDRIVE NO.: 6.

COLLECTOR TILT: 45.00 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 40.92 (DEGREES) RUN DATE: 02/05/80

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1277.	428.	0.33490	1.591	681.	1200	0	26.
FEB	1745.	649.	0.37186	1.394	905.	1044	0	28.
MAR	2356.	966.	0.41007	1.184	1143.	893	0	36.
APR	2998.	1357.	0.45264	0.997	1353.	495	0	49.
MAY	3455.	1667.	0.48233	0.876	1460.	231	36	59.
JUN	3643.	1840.	0.50509	0.825	1518.	33	132	68.
JUL	3544.	1788.	0.50459	0.847	1515.	9	217	72.
AUG	3170.	1596.	0.50358	0.946	1510.	16	131	70.
SEP	2584.	1272.	0.49222	1.128	1435.	101	62	64.
OCT	1922.	907.	0.47190	1.396	1266.	367	6	53.
NOV	1385.	505.	0.36464	1.573	794.	729	0	41.
DEC	1150.	354.	0.30774	1.611	570.	1104	0	29.

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

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